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RESEARCH MEMORANDUM

INVESTIGATIONS OF SLOT CONFIGURATIONS FOR FILM-COOLED TURBINE BLADES BY FLOW VISUALIZATION METHODS

By E. R. G. Eckert, Thomas W. Jackson
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Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
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SUMMARY

The film-cooling method as applied to turbine blades creates a film of cooling air outside the blade surface that acts as an insulating layer between the hot gas flow and the blade. The cooling-air film is usually generated by air jets blown from slots in the turbine-blade wall. In designing such a slotted turbine blade, a very great variety of slot configurations can be conceived. A useful and quick procedure for obtaining qualitative information on the effectiveness of different slot configurations is to make the flow of the cooling air visible. Two methods were used for this purpose; the first method utilized the traces caused by a reaction between paint spread over the blade surface and a gas mixed with the cooling air; the second method utilized smoke mixed with the cooling air to make it visible. Both methods were used to study cooling films built up on the trailing and leading edges of turbine blades. Films generated by rows of cooling holes flush to the blade surface, rows of holes ending in grooves, and slots were studied. From the visual observations, the use of a continuous slot as a means of creating the cooling film over the blade surface appeared to be superior to the use of holes or grooves.

INTRODUCTION

The usual method of cooling gas-turbine blades is to blow cooling air through the hollow interiors of the blades. The cooling air is usually introduced at the roots of the blades and discharged at the blade tips into the hot gas stream. In order to utilize the cooling air more effectively, either inserts are provided that direct the cooling air along the internal blade surface or the internal surface area is increased by fins. Wall temperature distributions, as measured in actual gas turbines, of two such blades, one with internal fins and the other one with the internal surface increased by tubes brazed into the interior of the blades, are shown in figure 1 (reference 1).

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Such turbine blades are cooled effectively along both sides but the temperatures of the leading and trailing edges still remain comparatively high.

One reason for the high leading-edge temperature is the high value of the gas-to-wall heat-transfer coefficient near the stagnation point of the gas flow. The calculated values of the local outside heat-transfer coefficients along various-shaped surfaces are shown in figure 2 (reference 2). This figure shows that the high values of the heat-transfer coefficient occur near the stagnation point. These high heat-transfer coefficients can be decreased by increasing the radius of curvature of the blade at the leading edge. Although increasing the radius of curvature at the leading edge of the blade also improves the conditions for the internal cooling-air flow in this region, it is doubtful whether this procedure alone will bring the leading-edge temperatures down to those obtained for the midchord regions.

The trailing edge is difficult to cool because aerodynamic considerations require a long thin section and there is difficulty in providing, with present blade-fabrication methods, a cooling-air passage near the trailing edge. The outside heat-transfer coefficients are high in this region because of high gas velocities and the conduction within the solid trailing edge is not effective enough to keep the temperatures at the end of the trailing edge at low values.

The method of film cooling, in which a layer of cooling air is created along the outside of the turbine blade, is an effective means of decreasing the temperatures near the leading and trailing edges. A report by Kueppers (reference 3) showed the effectiveness of cooling films created by slots in the blade surface and references 4 to 6 deal especially with the problem of finding effective slot configurations near the leading edge. These reports indicate that a continuous slot is the configuration that creates a film most effective for keeping the blade surface cool. Wieghardt in Germany also found that for a hot-air discharge for de-icing of wings a continuous slot gave the best results (reference 7).

As indicated by references 3 to 7, a continuous slot is the configuration that creates the most effective film. On the other hand, with regard to rigidity of the blade against vibrations, a configuration composed of short slots or holes would be more desirable than a continuous slot. An investigation into the possibilities of creating effective cooling films by configurations other than a continuous slot should therefore be useful.

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Two methods of flow visualization are described herein that were used to obtain quick qualitative information on the effectiveness of different slot configurations.

The cooling-air film along the outside of the blade acts essentially as an insulation. It is to be expected, therefore, that the parts of the blade surface that are well covered by the cooling air are kept cool. One method, which makes these regions visible, is applying a paint to the blade surface that changes its color under the influence of a chemical mixed with the cooling air. In this method, the cooling air was passed over concentrated ammonium hydroxide. A similar method is used in reference 4; the only difference is the use of hydrogen sulfide mixed with the outside gas flow. A second method, which was found useful, is to indicate the cooling-air coverage by mixing smoke with the cooling air. After leaving the slots, the cooling air begins to diffuse into the outside gas stream by a turbulent mixing process. The more the cooling air is diffused, the less effectively it insulates the surface. The amount of mixing between the cooling air and the hot gases is indicated by the intensity of the smoke at any place in the gas stream.

The film cooling of trailing edges as generated by rows of holes flush to the blade surface, by rows of holes ending in grooves in the blade surface, and by slots was studied. Leading-edge sections containing screens to simulate a porous material, chevron and vertical slots, and a capped row of holes were also investigated.

Experiences with both visualization methods are described in the following sections. Both methods proved useful in developing slot configurations for film-cooled turbine blades. Some general results obtained by this flow visualization study are presented.

INVESTIGATIONS USING COLOR-INDICATOR METHOD

Bromcresol purple was used as a color indicator. It was made up into a paint with a masking pigment, titanium dioxide, using alcohol, water, and glycerine acidified with sulfuric acid. The blade surface to be investigated was covered with this paint. Ammonia vapors were introduced into the cooling air by passing it over concentrated ammonium hydroxide. Under the influence of the ammonia vapors, the paint changes its color from yellow to purple. In this way, the coverage of the blade surface by the cooling-air film is revealed. A disadvantage of this method is that faint traces of ammonia can change the color of the paint. The effectiveness of the cooling-air film can therefore be easily overestimated.

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In order to avoid free convection currents, the molecular weight of the gas mixed with the cooling air should be close to the molecular weight of the air. This condition is not fulfilled by ammonia. Because the ammonia concentration in the cooling air is low, however, this influence can probably be neglected for the qualitative tests.

The advantage of the color-indicator method is that the experimental setup can be built with turbine blades of the original size and that outside gas velocities as high as in the real turbine can be used.

Experimental Setup

The experimental setup used for this method is shown in figure 3. It consists essentially of a static cascade containing four turbine blades (fig. 4). For precise investigations in a static cascade a larger number of blades should be used; however, because the cascade with four blades was readily available and because of the qualitative character of the tests, it was used for the described investigations. Compressed air is blown through the cascade and discharged into the test cell. The blade indicated in figure 4 contains the slot configuration to be tested. Cooling air is supplied from a compressed-air duct to the interior of this blade. In the tests, the outside air and the cooling air had the same temperature. Nevertheless, the expression "cooling air" will be used herein to discern the air that flows through the cooling configurations from the outside air stream. Ammonia was mixed with the cooling air in the manner mentioned before. The velocities of the outside air and the cooling air and the pressures were measured by manometers visible on the left side of figure 3. The Mach number in the blade passage was varied in the range from 0.1 to 0.95.

Six cooling configurations were tested with the color-indicator method. They are described in the section "Discussion of Configurations and Results" in conjunction with the results obtained.

Discussion of Configurations and Results

The blade configuration used for these tests, the inlet angle under which the air was directed against the cascade, and the locations

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of the configurations used to distribute the cooling air are shown in figure 4. Photographs were taken of the blade in the directions indicated by arrows A and B in figure 4 to show the film coverage of the blade surface with coolant air, as indicated by the change in the color of the paint. Such photographs for different coolant-flow-passage configurations are shown in figures 5 through 10.

In figures 5 and 6, the coolant passages consist of rows of holes with large and small spacings. The photographs indicate that the jets of cooling air discharged from the holes spread into the outside air flow. The angle at which this spreading occurs was found to be almost the same as the one determined by A. Kuethe (reference 8) for the turbulent mixing of jets whose velocity component parallel to the blade surface in leaving the holes is assumed small as compared with the outside air velocity. Obviously, at some distance downstream of the holes, a more or less continuous air film can be created. The distance from the holes where this occurs depends on the distance between the holes. The tests with the smoke-visualization method, which are described later, indicate, however, that such a film is much diffused by the main gas flow and is not as effective as a film created by a continuous slot.

In order to cover the space between the holes with cooling air, a groove was provided on the blade as shown in figure 7. The change in color of the paint indicates that it is possible in this way to cover the whole surface of the blade downstream of the holes with some cooling air. Experiments with smoke, which are described subsequently, however, revealed that this is one example where the color-indicator method leads to overestimating the cooling effectiveness. The cooling-air film between the holes was diffused and measurements of the surface temperature of a turbine blade cooled in such a way showed unsatisfactory cooling.

Another configuration where a number of holes drilled from the inside surface of the blade discharge into a continuous slot cut at an oblique angle in the outside surface of the blade wall is shown in figure 8. This photograph indicates good coverage. A similar configuration subsequently discussed was investigated in the smoke tunnel. Figures 5 through 8 contain photographs of the pressure side of the blade.

A photograph of the suction side of a blade is shown in figure 9. The paint changed color not only downstream but also upstream of the coolant holes. This change obviously indicates a backflow caused by a separation. The same type phenomenon probably caused the coloring

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shown in figure 10 where the cooling air blown out through holes ending in grooves near the leading edge at first colors single streaks along the blade surface but later combines into one continuous streak at some location downstream of the holes. The place where the separation occurs obviously depends on the Reynolds or Mach number of the flow because it changed its position with varying outside air velocity. A higher velocity caused the place of separation to move downstream. Such a separation of the flow on the suction side of turbine blades near the trailing edge was detected in schlieren and interference photographs as well. It seems to occur quite often.

From the color-indicator method, it cannot be judged if the mixing process in the dead-water region behind the separation makes the cooling-air film ineffective. Measurements by Kueppers (reference 3) showed comparatively low blade surface temperatures at a place where obviously separation occurred, which seems to indicate that the coverage in the separated region is still reasonable. On the other hand, this observation was made on a static two-dimensional cascade. It may be that radial flow, which most likely occurs in the separated region in the real turbine, changes conditions completely. As long as no knowledge exists on these phenomena, arranging the cooling slots near the trailing edge on only the pressure side of the turbine blade seems advisable. The coolant film created in such a way on the pressure side has the additional task of carrying away the heat that flows into the trailing edge of the blade on the suction surface.

INVESTIGATIONS IN SMOKE TUNNEL

In order to make the smoke, which in this method is mixed with the cooling air, clearly visible, only low outside and cooling-air velocities under 25 feet per second were used. In order to attain approximately the same Reynolds number in the test setup used for this method as in the application on an actual turbine blade, the slot configurations were investigated in an increased scale. The increased scale also favors visual observation. The Mach number in the smoke tests differed, of course, from that in a turbine. The Mach number, however, is probably of secondary importance for the mixing process as long as shock waves are avoided so that disregarding the Mach number for these qualitative tests seems permissible. No temperature differences between the outside air stream and the cooling air were present in the tests. A possible influence of this temperature difference is therefore not revealed by the tests.

Experimental Setup

The setup used for these tests is a wooden wind tunnel with a cross section 8 by 11 inches. The wind tunnel is shown in figure 11. Air is sucked from the test cell into the tunnel, which is essentially a duct of rectangular cross section. At a certain distance from the inlet nozzle, the tunnel walls are made of Lucite so that the flow in the tunnel can be observed. In figure 11, a number of streamline-shaped models can be observed on top of the bottom wall in the plastic section of the tunnel. They were used for studies of the flow near the leading edge of turbine blades. These studies are discussed later.

In the experiments studying the behavior of slots near the trailing edge of blades, the configurations tested were located in the bottom wall of the plastic section of the tunnel. This section is removable to facilitate changing experimental configurations. The slot configurations provided in the bottom wall section represent slots near the trailing edge of a turbine blade. Therefore, the length of the tunnel from the inlet to the place of observation was chosen to correspond approximately to the blade chord length in the increased scale.

The wall forming the top part of the tunnel can be rotated around an axis near the inlet. In this way, constant, decreasing, or increasing pressure gradients can be adjusted along the flow.

The smoke is generated by burning cigars that were treated with oil. The cooling air is blown through these cigars and then passes through a filter before it enters a chamber below the bottom wall test section of the tunnel containing the slot configurations. The air velocity in the tunnel and the amount of cooling air are measured by the manometers shown on the left side of the photograph and by a rotameter.

Five trailing-edge cooling configurations and four leading-edge configurations were tested in the smoke tunnel.

Discussion of Configurations and Results

Trailing-edge configurations. - Figures 12 through 24 show trailing-edge configurations which have been tested and results of the tests. At first a continuous slot was investigated in order to obtain, from a photograph of the cooling-air film created in this way, a standard with which the other configurations can be compared. Figure 12 shows this slot configuration. Figure 13 shows the coolant

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film as observed by looking at an oblique angle toward the slot, and figure 14 shows the coolant film as observed when looking normal to the flow direction and tangentially to the bottom surface of the tunnel.

In the photographs contained in figure 14, the ratio of the cooling-air velocity to the outside air velocity is changed. This ratio is the most important factor influencing the mixing process of the coolant and the main gas stream. Experiments reported in references 4 through 7 showed that the cooling effectiveness is highest when the ratio of the coolant velocity coming out of the slot to the outside air velocity is near 1.

Close observation of figure 14 shows that the smoke intensity at the far downstream end is greater for the larger velocity ratios. This indicates an increasing cooling effectiveness for increasing velocity ratios. It can also be observed that the coolant film adheres very closely to the surface. The thickness of the coolant film does not seem to vary much with the ratio of the coolant velocity to the outside velocity.

A coolant passage consisting of a single row of holes and the photographs that were obtained with this coolant-passage arrangement are shown in figure 15 and 16, respectively. In the photographs, again the ratio of the coolant to the outside air velocity is changed. Figure 16 reveals that the jets of cooling air coming out of the holes do not contact the surface, especially at high coolant velocities. No continuous film of coolant that adheres to the surface is created by a row of holes. The first photograph in figure 16 shows what appears to be a coolant film that adheres to the surface. This film, however, is not uniform in the direction normal to the figure but is made up of single streaks of coolant air similar to those illustrated in figures 5 and 6. In figure 16, the smoke intensity in the film appears denser at small velocity ratios of cooling air to main flow. This occurrence contrasts with all the other observations and may be caused by the decrease in smoke production during this run.

A row of oblique holes emptying into a groove does not improve conditions very much. This cooling arrangement and photographs of the smoke film created in such a way are shown in figures 17, 18, and 19. Figure 18 indicates that the groove does not create a continuous film of cooling air. Close visual observation revealed that some traces of smoke were brought by the groove into the regions between the holes. The smoke intensity between the holes is too low to be observed in the photograph in figure 18. It explains, however, the difference between this photograph and figure 7, which was obtained by the color-indicator method.

In connection with the problem of de-icing of airplane wings, Wieghardt (reference 7) made investigations of continuous and interrupted slots. The configurations tested by Wieghardt in a wind tunnel similar to the one shown in figure 11 are shown in figure 20.

Wieghardt used a heated air jet emerging from the slot and measured the temperatures of the wall of his wind tunnel downstream of the slot. He obtained temperature distributions as shown in figure 21 where the ratio of the differences, wall temperature T_w minus air-stream temperature T_a, and slot-air temperature T_s minus air-stream temperature T_a, is plotted over a distance x from the slot exit in a downstream direction. The ratio of the velocity of the air leaving the slot to the velocity in the air stream for these tests was near 1.

As expected, the temperature of the wall, which equals the temperature T_s at the place where the air leaves the slot, decreases in the downstream direction as the air coming out of the slot is diffused by mixing with the outside air. The continuous slot gave temperatures as shown in configuration A, figure 21. The two curves marked B show the results of the temperature measurements on locations 1 and 2 (fig. 20, configuration B) behind and in between the interrupted slots, and curve C presents the temperatures behind a double row of slots as shown under configuration C, figure 20. It can be seen from the curves in figure 21 that interrupted slots, even in a double-row arrangement, are much inferior to a continuous slot.

A ducted groove similar to the continuous slot in figure 12 is shown in figure 22, section A-A, with the only difference being that the cooling air is fed by a row of holes into the groove. One peculiar observation was made with this arrangement. The highest smoke intensity in the coolant film did not occur behind the holes as was expected but half way in between the single holes. By proper choice of the slot widths and the distance between the holes, it may be possible to obtain a smoke film that is almost of uniform intensity along the slot. Because it is difficult to manufacture such a slot on a turbine blade, this investigation was discontinued. The corresponding smoke photographs for this configuration are shown in figure 23.

A comparison of the results shown in figure 23 with those in figure 14 indicates clearly that the cooling effect of this arrangement does not reach as far downstream as that due to the configuration shown in figure 12. Figure 23 also indicates, by the darker shade of the smoke near the surface, some separation of the smoke film from the surface.

A configuration that was an attempt to obtain better distribution of the cooling air coming out of a row of holes by using a very large groove is shown in figure 22, section B-B. Figure 24 presents the corresponding smoke photographs. This attempt proved unsuccessful because the flow is very turbulent behind the groove and no continuous cooling film is created in this way. The photographs in figure 24 may be misleading because they do not indicate the magnitude of the turbulence. In reality, visual observation showed a very pronounced fluctuation in the smoke pattern. In the photographs, this fluctuation is indicated by the width of the smoke stream.

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The turbulence created by this configuration indicates that it is quite important to design the slot configurations so that the outside flow is disturbed as little as possible by the cooling air. Any vortices created in the outside flow, for example those due to the groove in configuration B-B, break up the coolant film.

Leading-edge slot configurations. - Figures 25 through 30 are concerned with an investigation of different slot configurations for the leading edges of turbine blades. For this purpose, four streamlined models were built of wood and placed vertically on top of the bottom plate in the wind tunnel. Each of the models had a different slot configuration near the leading edge. Figure 25 shows the shape of the models and the slot arrangements in them. It is to be expected that the flow would separate from the surface of the models somewhere near the place of maximum thickness. This separation, however, should not influence the conditions near the stagnation point enough to make the qualitative conclusions drawn from these studies invalid.

Model A was to represent a porous wall near the leading edge. The porous part of the wall is made by a number of screens placed one on top of the other. Model B has inclined slots, model C has vertical slots, and model D has two openings on the stagnation line which are covered by a cap. The cap was fastened to the model by three pegs.

Photographs of the smoke film generated by the inclined slots are presented in figures 26 and 27. Figure 26 was obtained with a high cooling-air flow rate and figure 27 with a low cooling-air flow rate. These photographs explain difficulties that were encountered in references 4, 5, and 6 in the development of slotted leading edges. Along the outside of the blades, the pressure is highest at the stagnation point and drops in downstream direction along the blade surface. The pressure inside the hollow blade is practically constant because of the low velocities. When the inside pressure is gradually

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increased, it therefore reaches the outside pressure first in the downstream part of the slot and starts the cooling-air flow in this region. By increasing the coolant flow rate, the slot region through which the coolant flow passes can be increased. The flow of the cooling air, however, will always be greatest in the downstream portion of the slot. The same difficulty in obtaining equal flow distribution arises in configuration C where the downstream slots get more coolant flow than the slots near the stagnation point.

The coolant film in a vertical slot can be seen in figure 28. Figure 29 shows the coolant film generated by two openings covered with a cap. (See fig. 25, configuration D.) The cap was fastened to the blade by three pins. The smoke intensity is comparatively uniform along the slot made by the cap; however, the same peculiar observation that was made on the simulated continuous-slot trailing-edge test section (fig. 22, section A-A) can be made here also; namely, that the highest smoke intensity does not occur behind the holes but half way between both holes. In figure 29 this place is downstream of the central peg. This larger smoke intensity near the peg occurred on both sides of the blade simultaneously.

The coolant film generated by the simulated porous leading-edge test section is shown in figure 30. As shown in the figure the cooling-air coverage is excellent.

CONCLUDING REMARKS

Flow visualization by the color-indicator method and by the smoke-addition method proved effective for obtaining quick qualitative results on the effectiveness of different slot configurations for film-cooled turbine blades.

A continuous slot gives the best coverage of the cooling-air film. Such a slot should therefore be approached in the design of film-cooled turbine blades by the use of slots with large ratios of length to spacing. Coolant-passage configurations using a row of holes alone or a row of holes in connection with a groove proved inferior to the continuous slot.

Slots near the trailing edge on the suction side of turbine blades are often in a region of flow separation. Secondary flow may disturb the coolant film in this region. Arranging the coolant air slots on the pressure side avoids these difficulties.

In designing slot configurations near the leading edge, the pressure distribution over the outside surface of the blade must be taken into consideration.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

REFERENCES

1. Hickel, Robert O., and Ellerbrock, Herman H., Jr.: Experimental Investigation of Air-Cooled Turbine Blades in Turbojet Engine. II - Rotor Blades with 15 Fins in Cooling-Air Passages. NACA RM E50I14, 1950.

2. Eckert, E.: Calculation of the Heat Transfer in the Boundary Layer of Bodies in Flow. Available as ATI 143691, CADO.

3. Kuepper, K. H.: Temperature Measurement on Two Stationary Bucket Profiles for Gas Turbines with Boundary Layer Cooling. Trans. No. F-TS-1543-RE, Air Materiel Command, U.S. Air Force, Jan. 1948. (ATI No. 18576.)

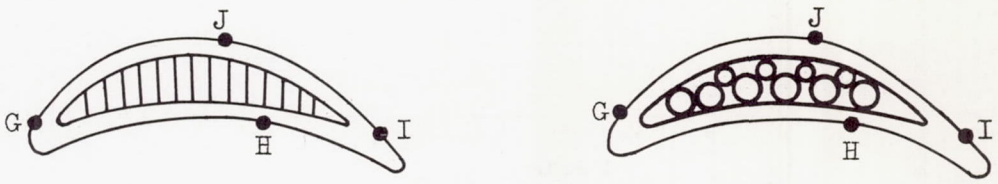
4. Scott, Harry J., Jr.: Turbine Blade Cooling (Final H_2S Test Report). Rep. No. 2036, Stalker Development Co., March 22, 1949.

5. Dempsey, W. W.: Turbine Blade Cooling (Final Hot Test Report). Rep. No. 2037, Stalker Development Co., June 29, 1949.

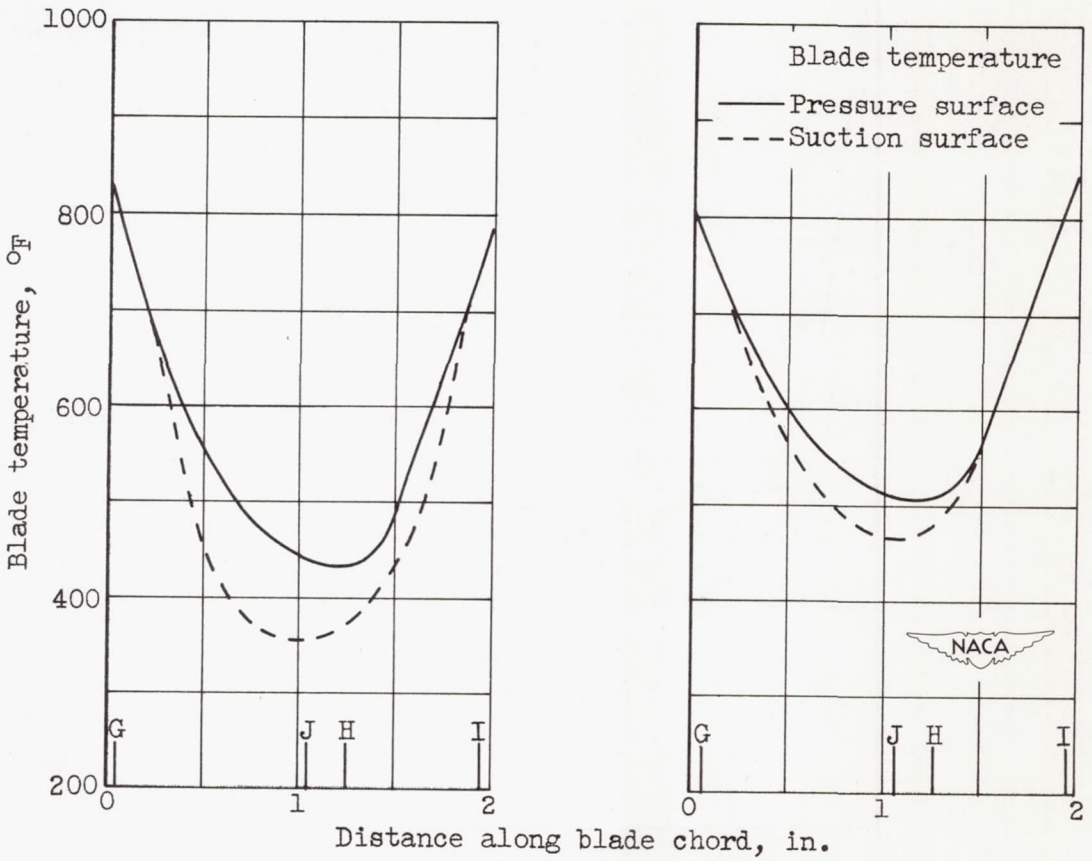
6. Scott, Harry J., Jr.: Turbine Blade Cooling (Final Cascade Test Report). Rep. No. 2038, Stalker Development Co., June 30, 1949.

7. Wieghardt, K.: Hot-Air Discharge for De-Icing. AAF Trans. No. F-TS-919-RE, Air Materiel Command, Dec. 1946.

8. Kuethe, Arnold M.: Investigation of the Turbulent Mixing Regions Formed by Jets. Jour. Appl. Mech., vol. 2, no. 3, Sept. 1935, pp. A87-A95.



Thermocouple locations



(a) 15-Fin blade. (b) 10-Tube blade.

Figure 1. - Temperature distributions in turbine blades. Effective gas temperature, 980° F; ratio of coolant weight to gas weight, 0.05; cooling-air temperature, 70° F.

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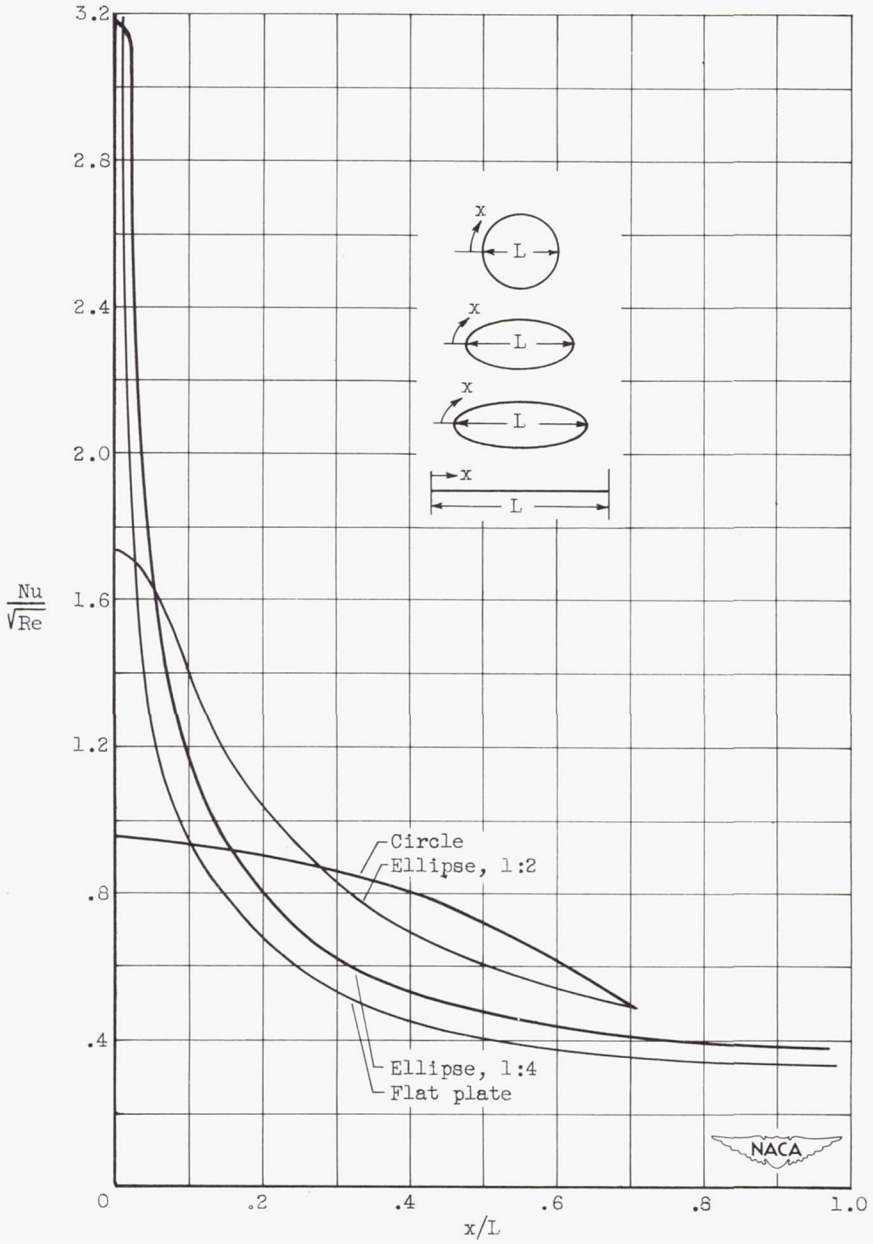

Figure 2. - Variation of heat-transfer coefficients for circular cylinder, two elliptical cylinders, and flat plate in laminar flow. Nu, Nusselt number based on length L; Re, Reynolds number based on length L and on stream velocity; x, distance from stagnation point along surface; L, length of object in flow direction.

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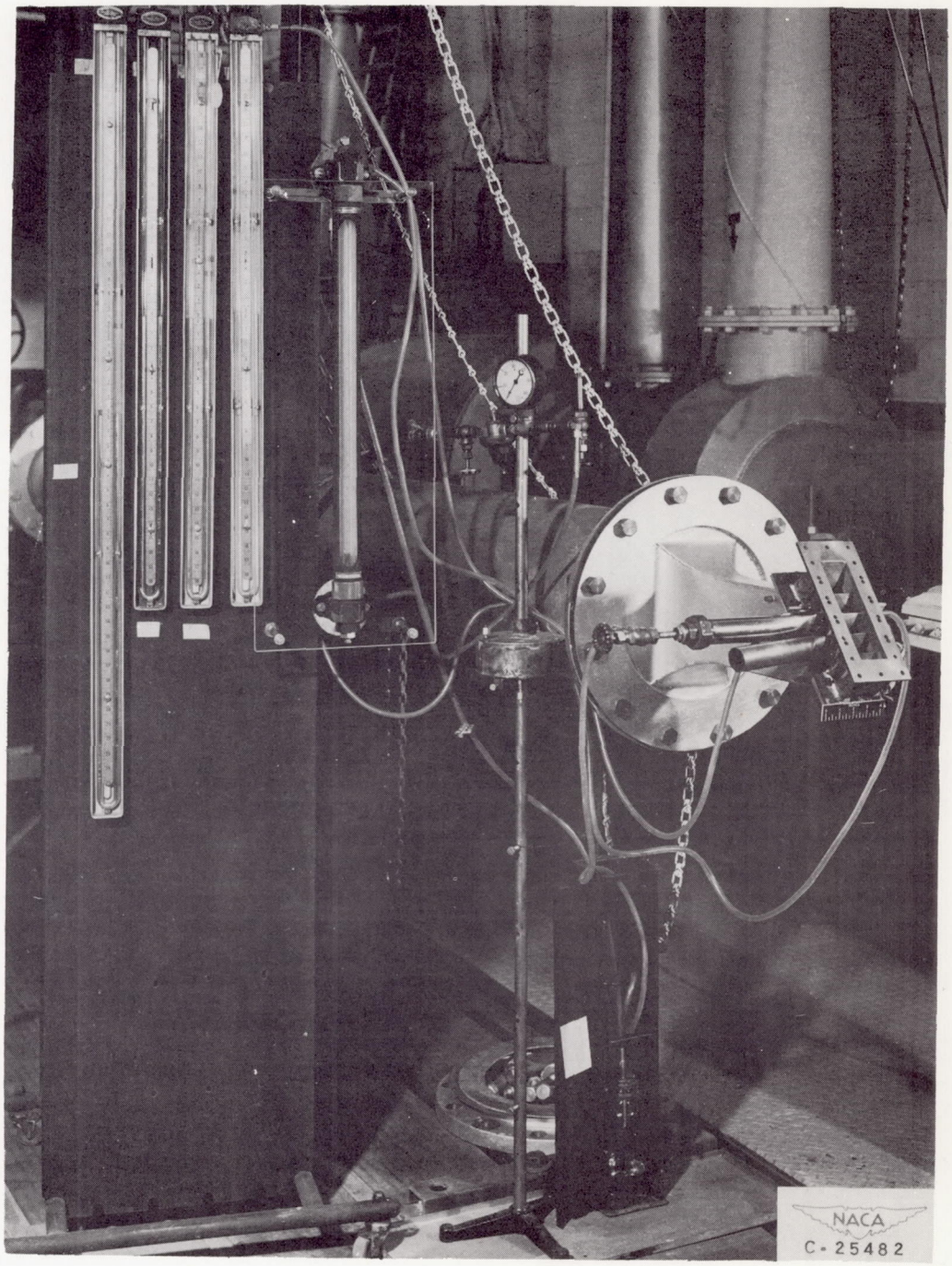


Figure 3. - Turbine-blade cascade used for color-indicator tests.

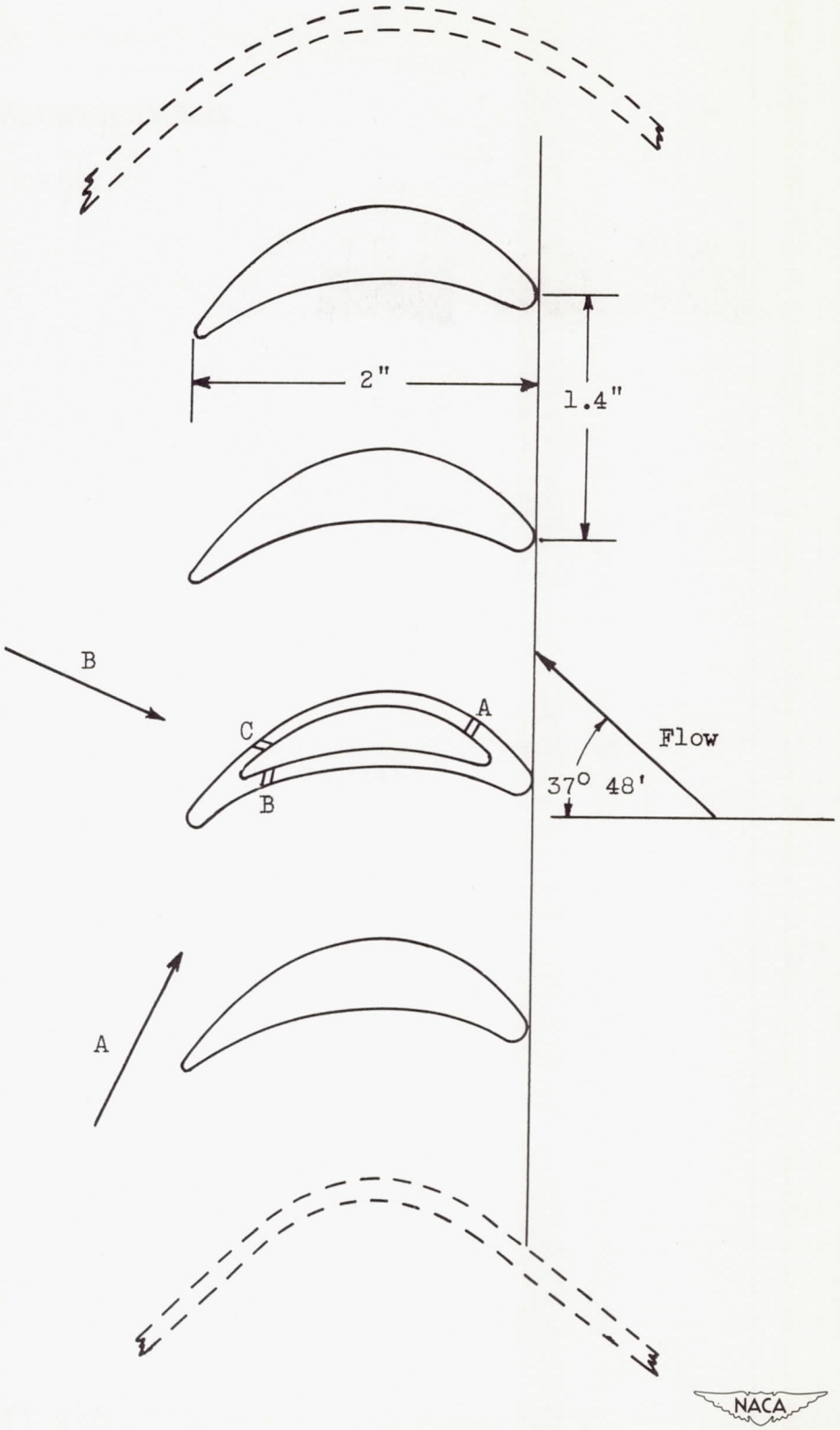
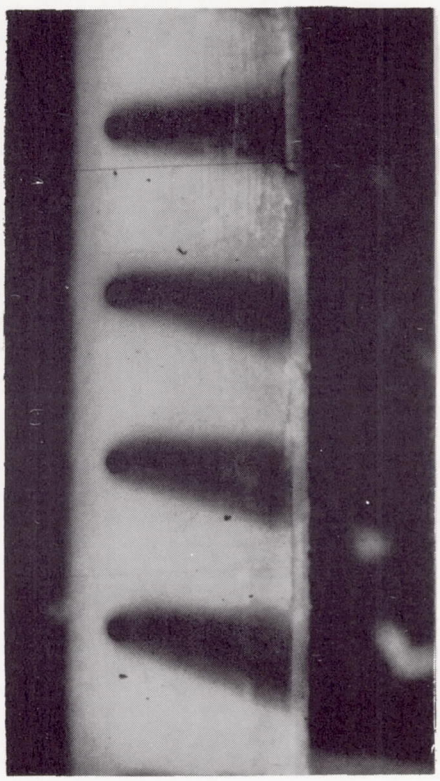


Figure 4. - Blade shape and coolant passage locations.



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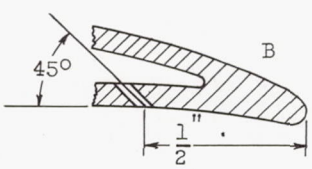
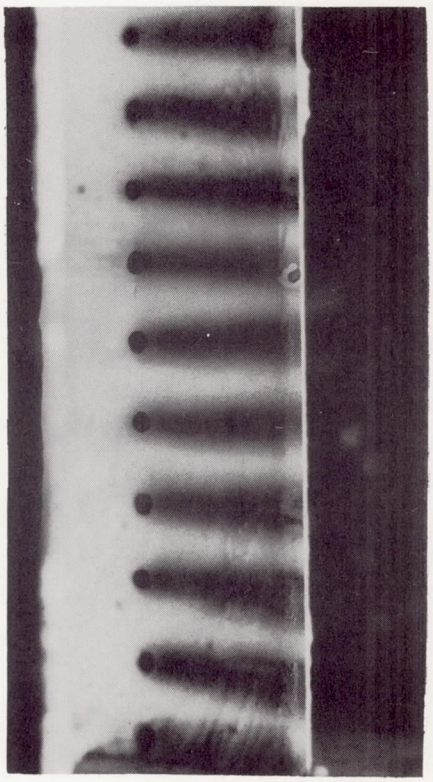


Figure 5. - Coolant coverage.

0.040-inch diameter holes
0.375-inch spacing



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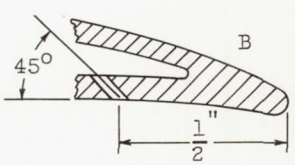
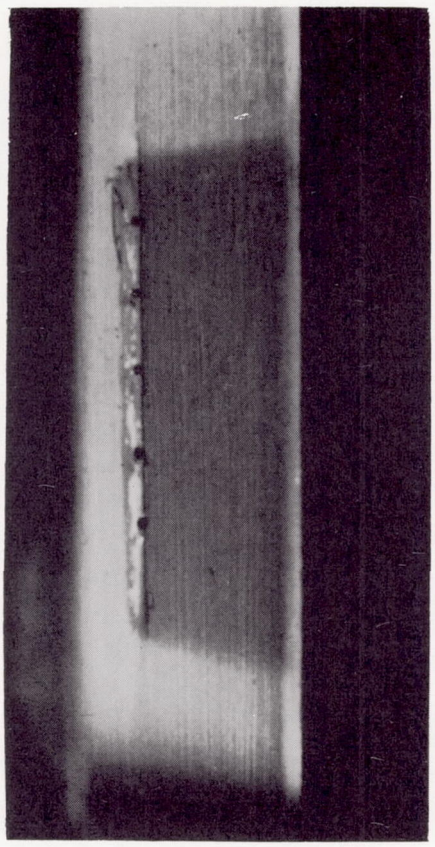


Figure 6. - Coolant coverage.

0.040-inch diameter holes
0.1875-inch spacing



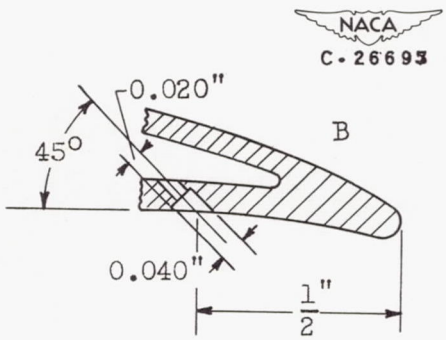
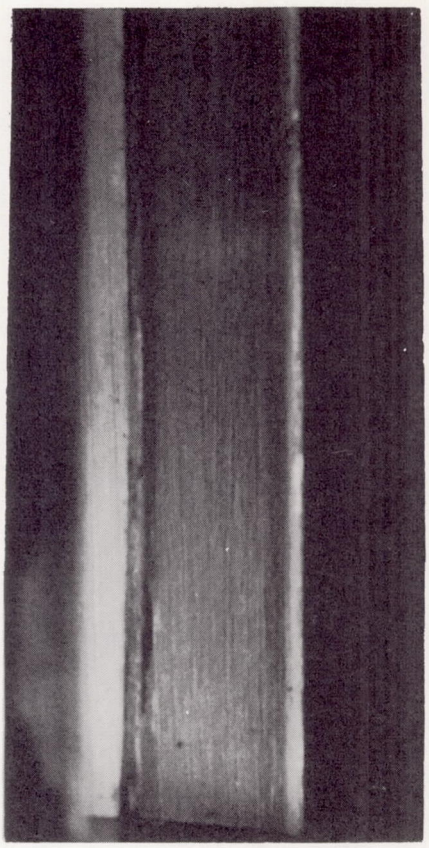


Figure 7. - Coolant coverage.

0.020-inch diameter holes
0.1875-inch spacing
Groove on outer surface



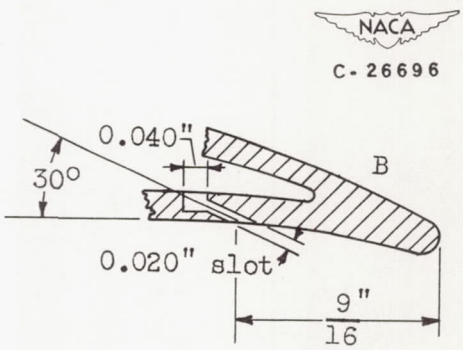
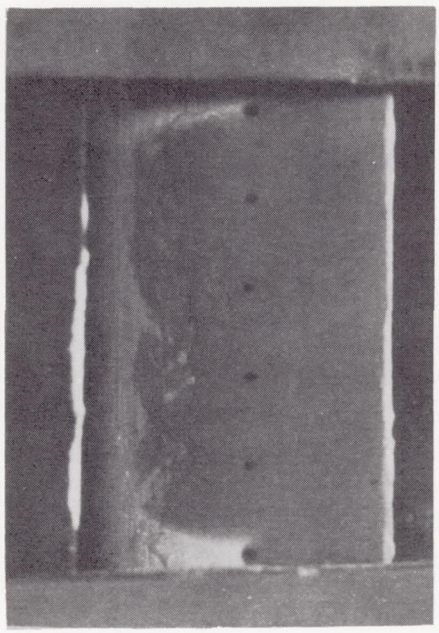


Figure 8. - Coolant coverage.

0.040-inch diameter holes
0.375-inch spacing
Holes open into 0.020-inch slot



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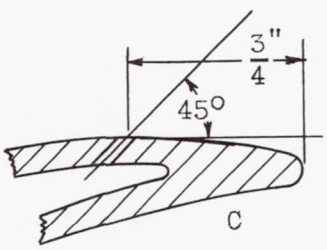
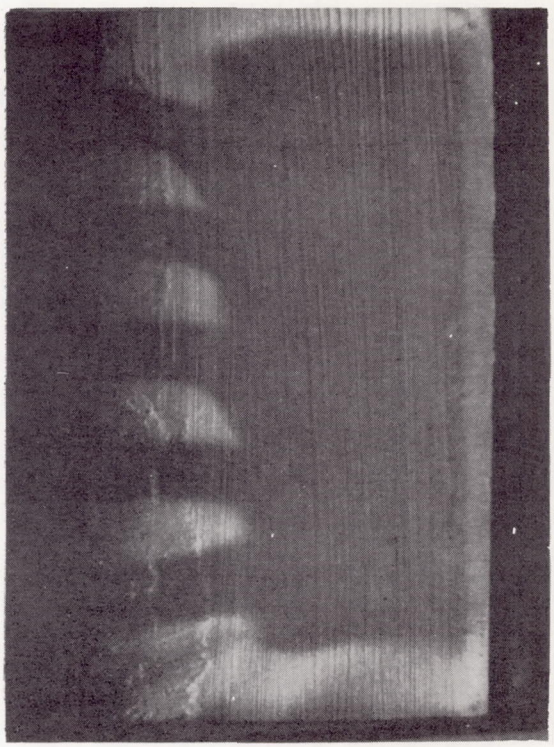


Figure 9. - Coolant covers showing reverse flow on suction surface.

0.040-inch diameter holes
0.375-inch spacing



NACA
C-26698

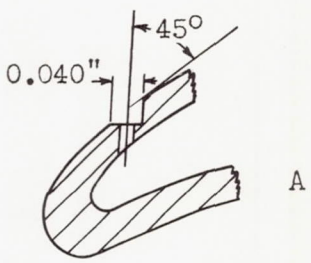


Figure 10. - Coolant coverage.

0.020-inch diameter holes
0.1875-inch spacing
Grooves on outer surface

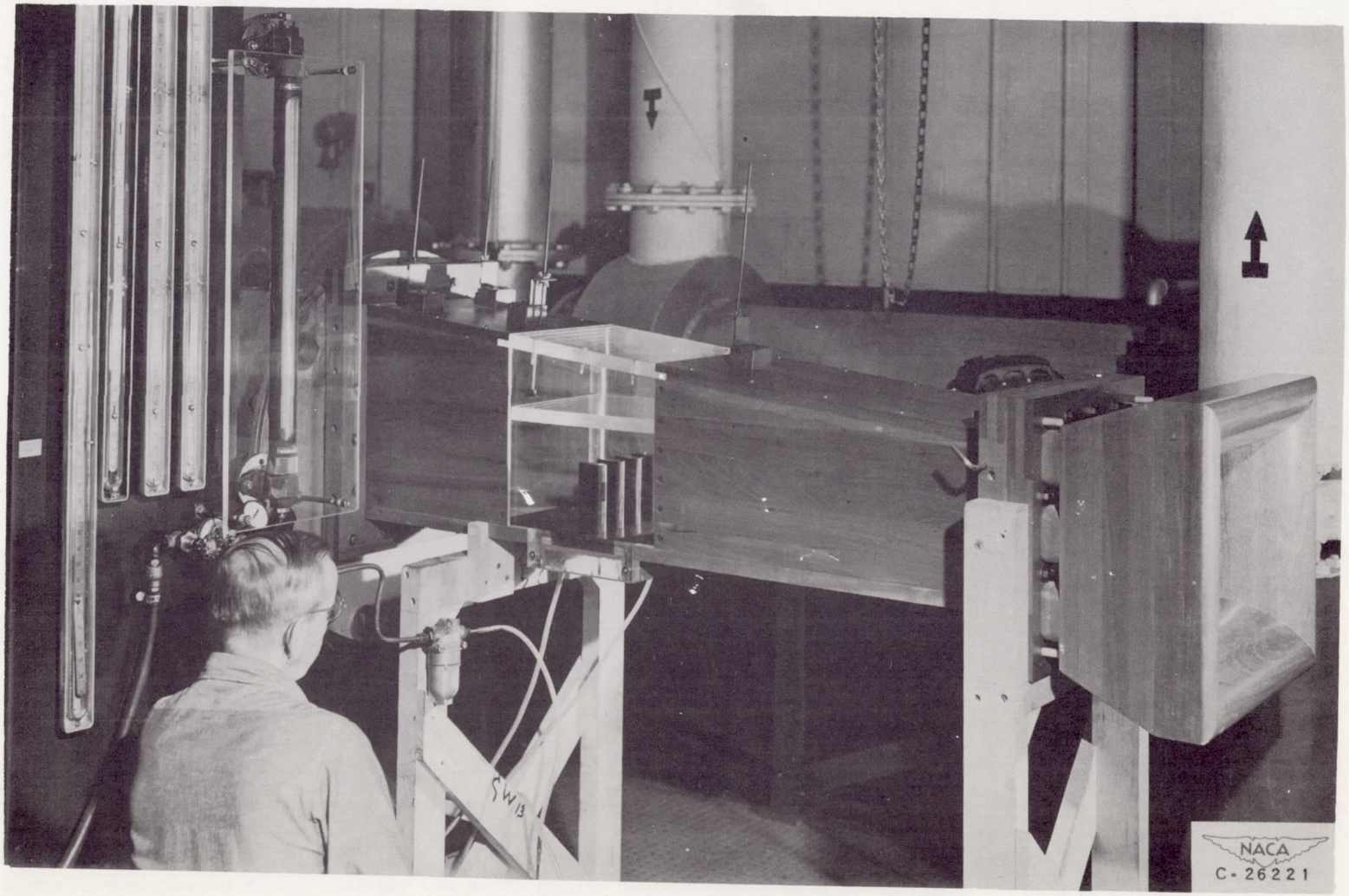


Figure 11. - 8- by 11-inch wind tunnel used for smoke tests. (Leading-edge test section mounted in tunnel.)

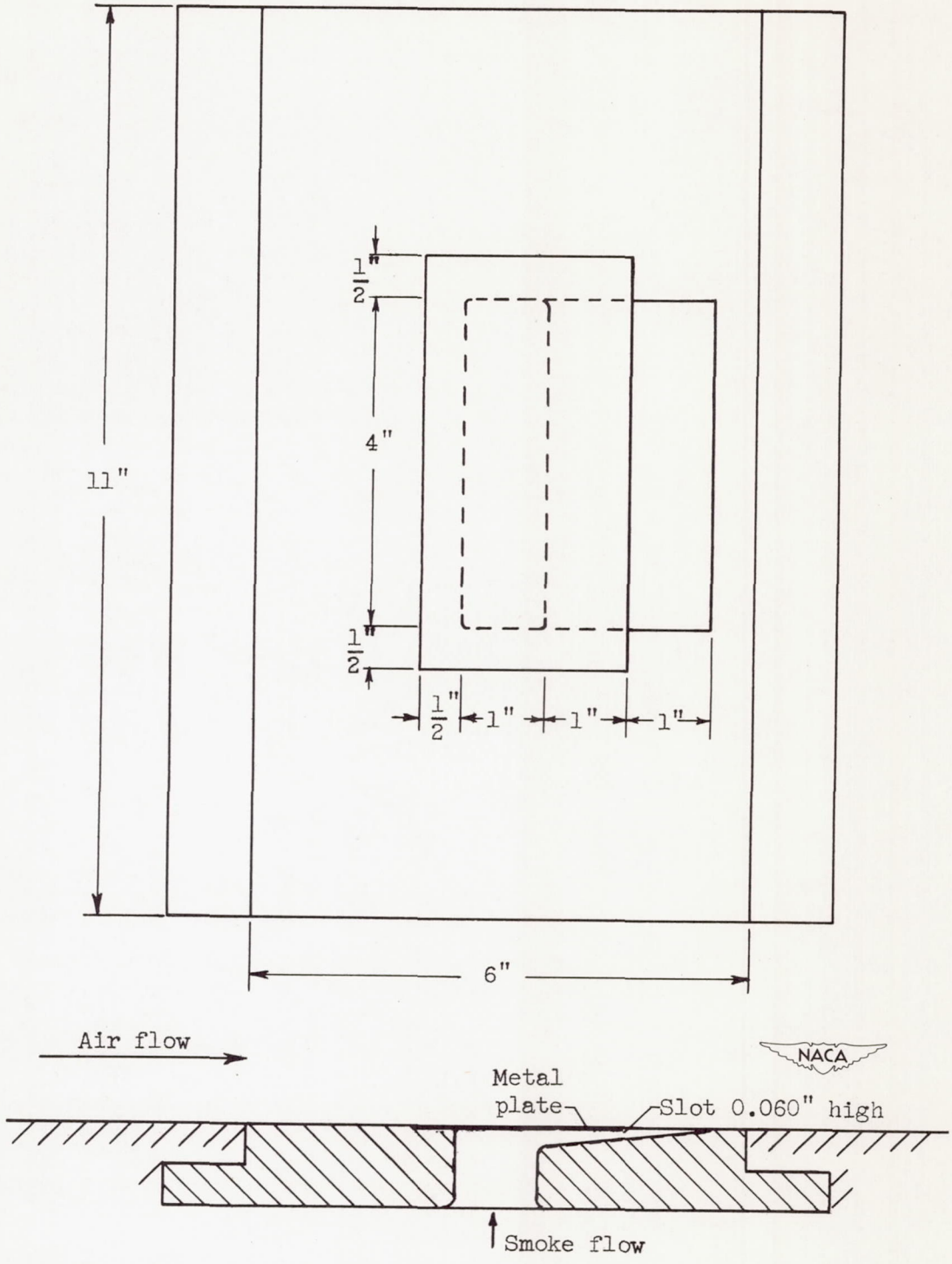


Figure 12. - Continuous-slot trailing-edge test section.

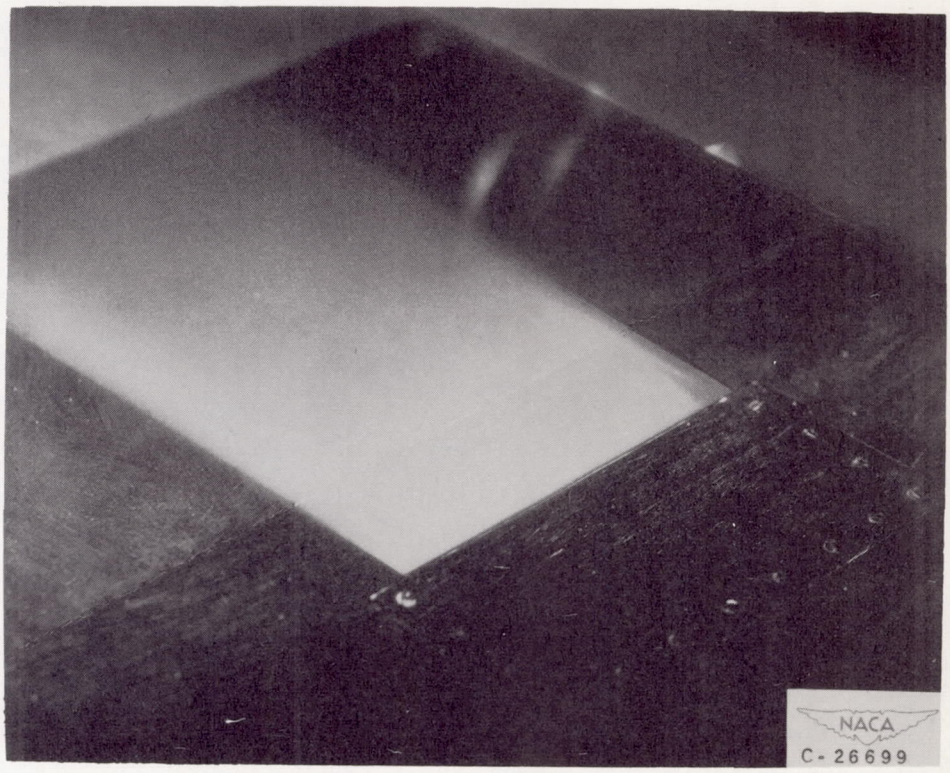


Figure 13. - Continuous-slot trailing-edge test section.

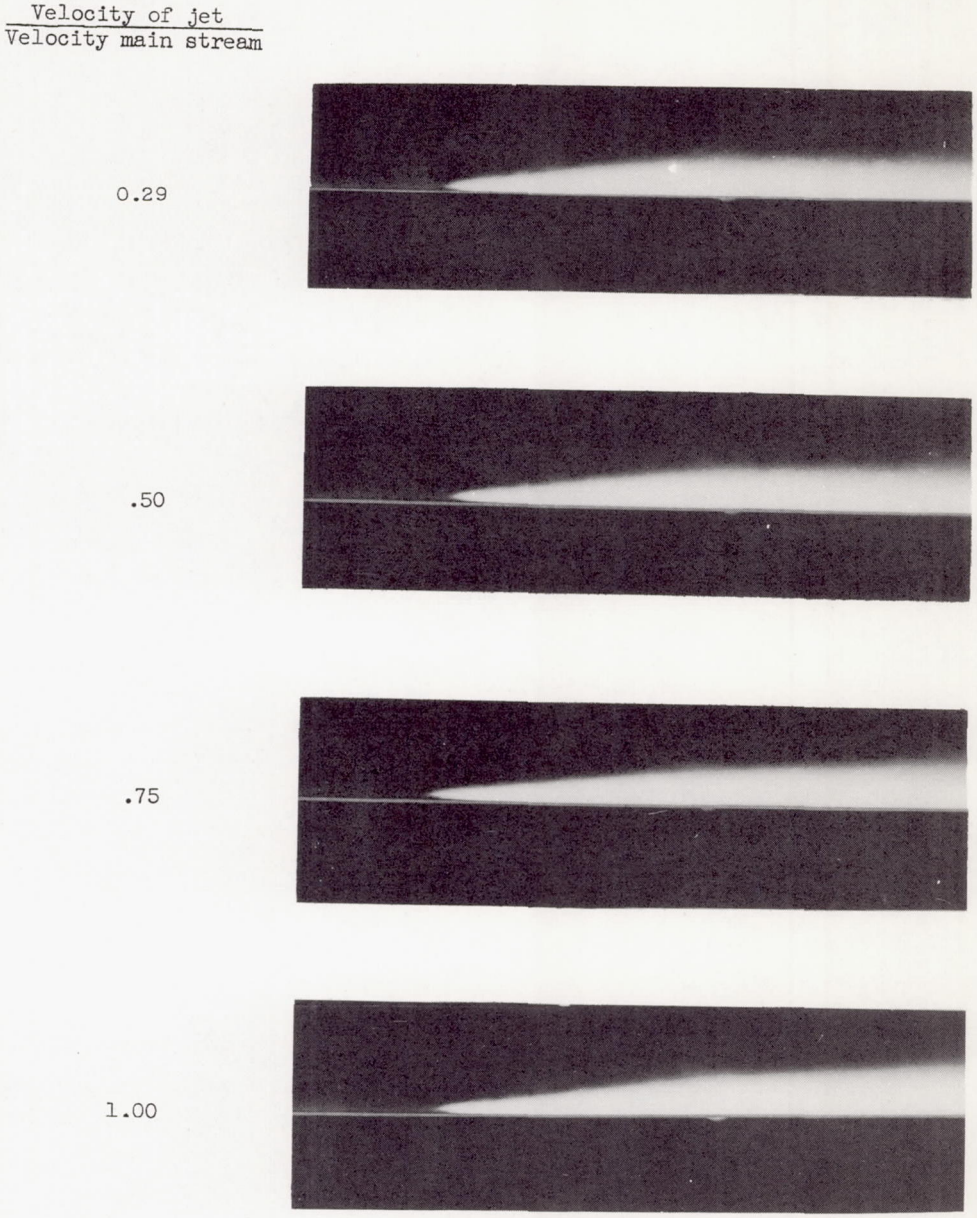


Figure 14. - Smoke jet for continuous-slot trailing-edge test section.

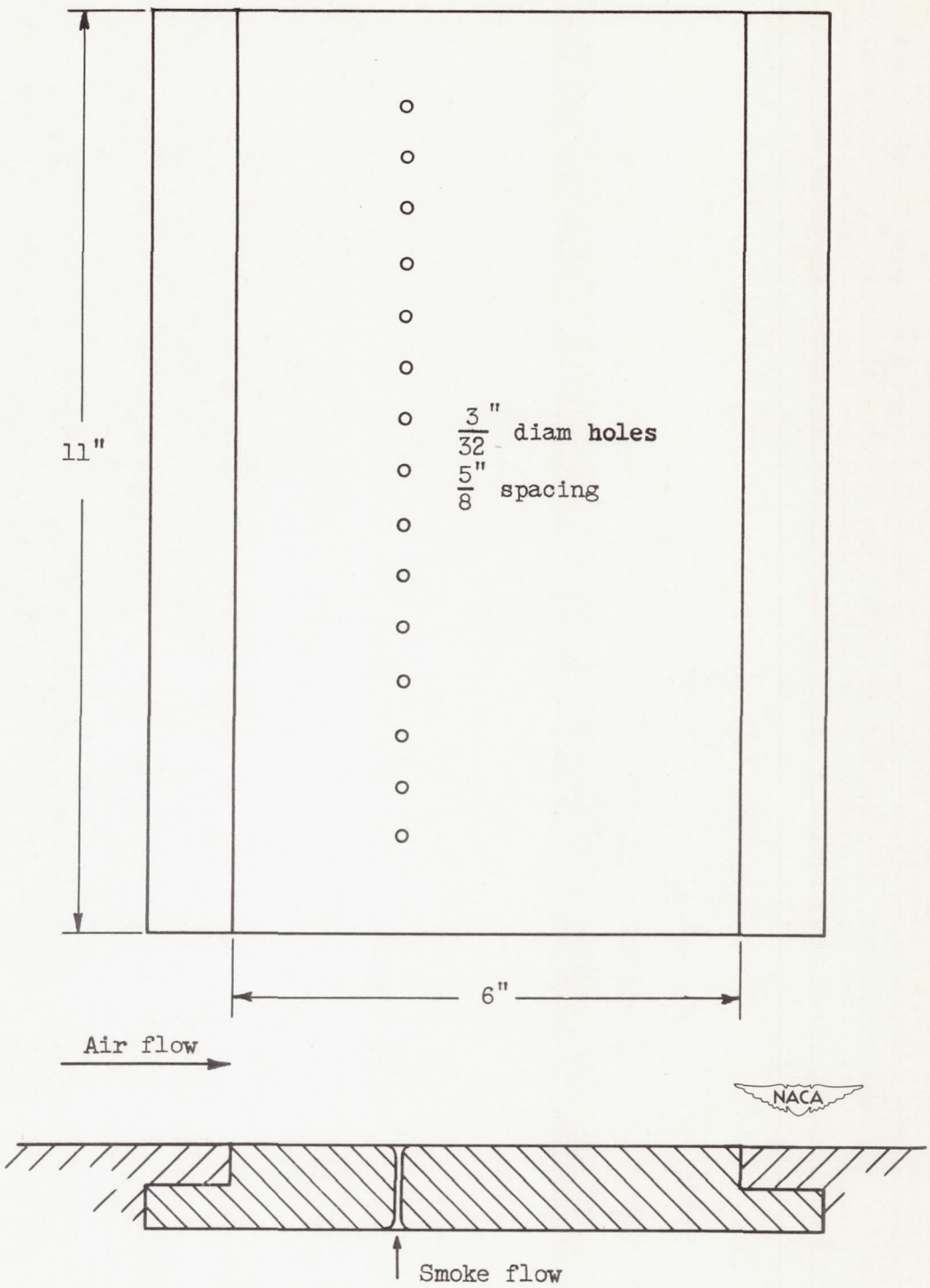


Figure 15. - Row-of-holes trailing-edge test section.

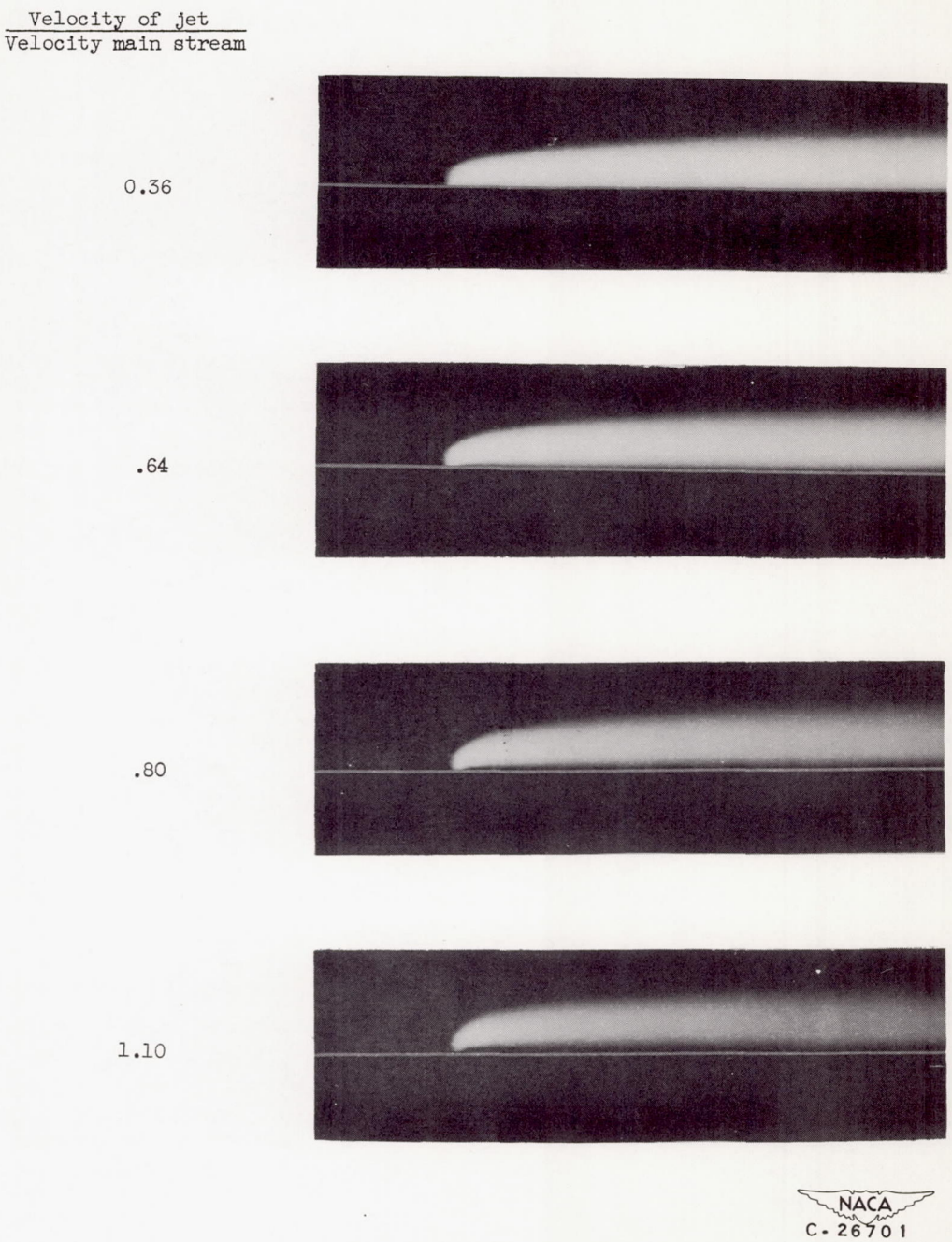


Figure 16. - Smoke jet for row-of-holes trailing-edge test section.

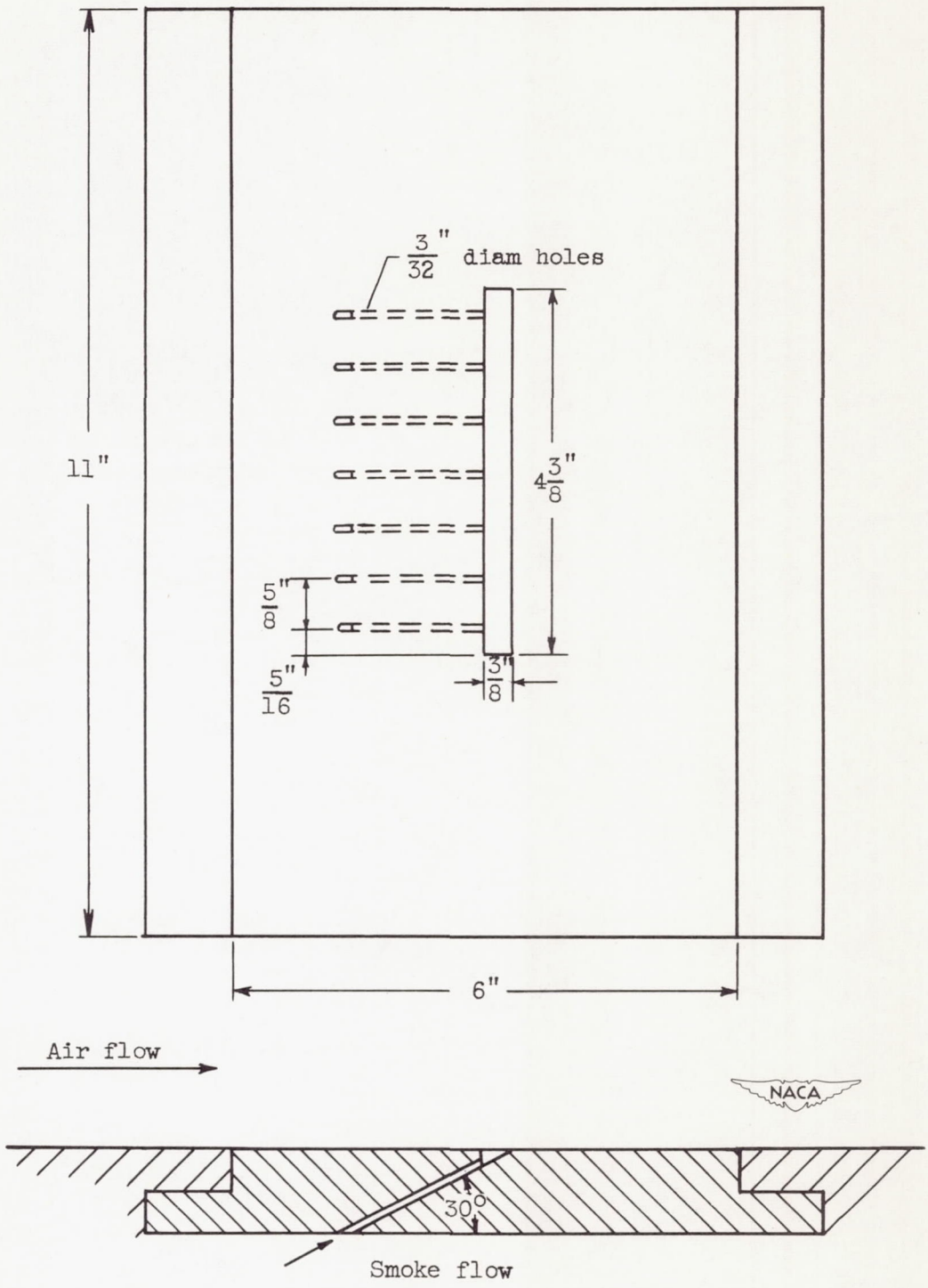


Figure 17. - Row of holes in groove trailing-edge test section.

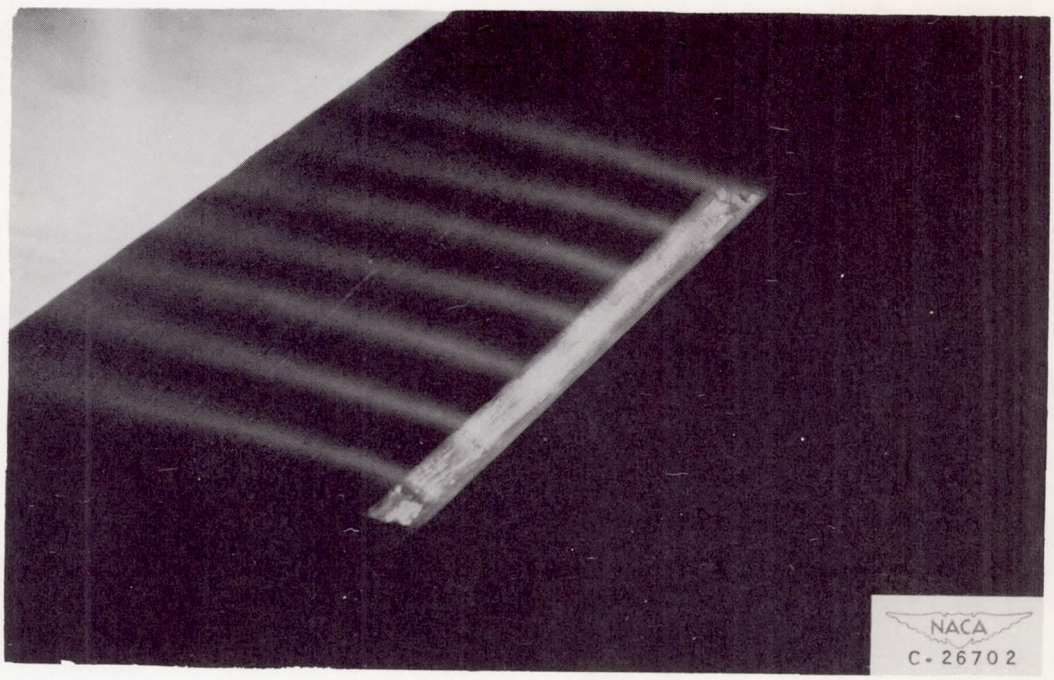


Figure 18. - Row of holes in groove trailing-edge test section.

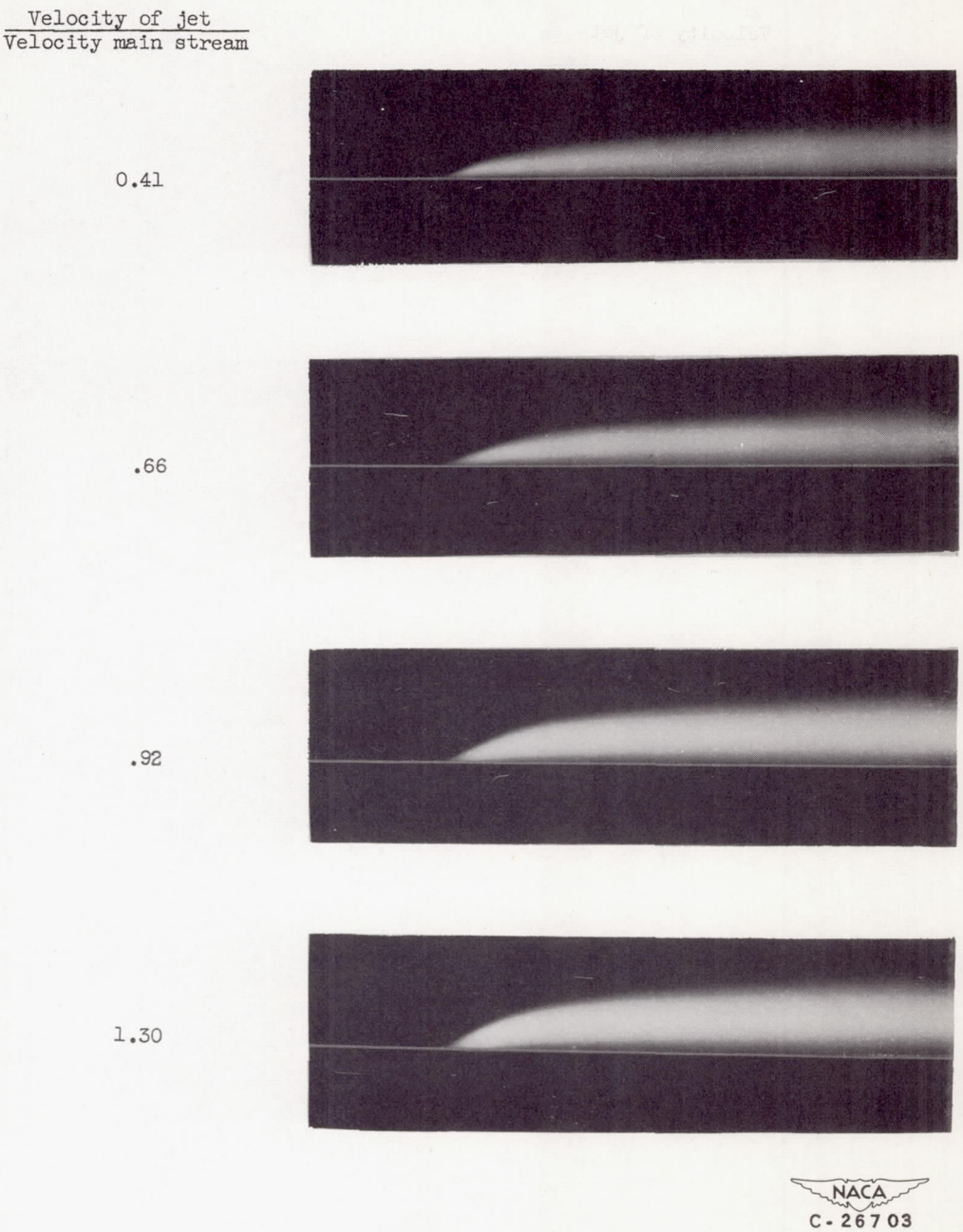


Figure 19. - Smoke jet for row of holes in groove trailing-edge test section.

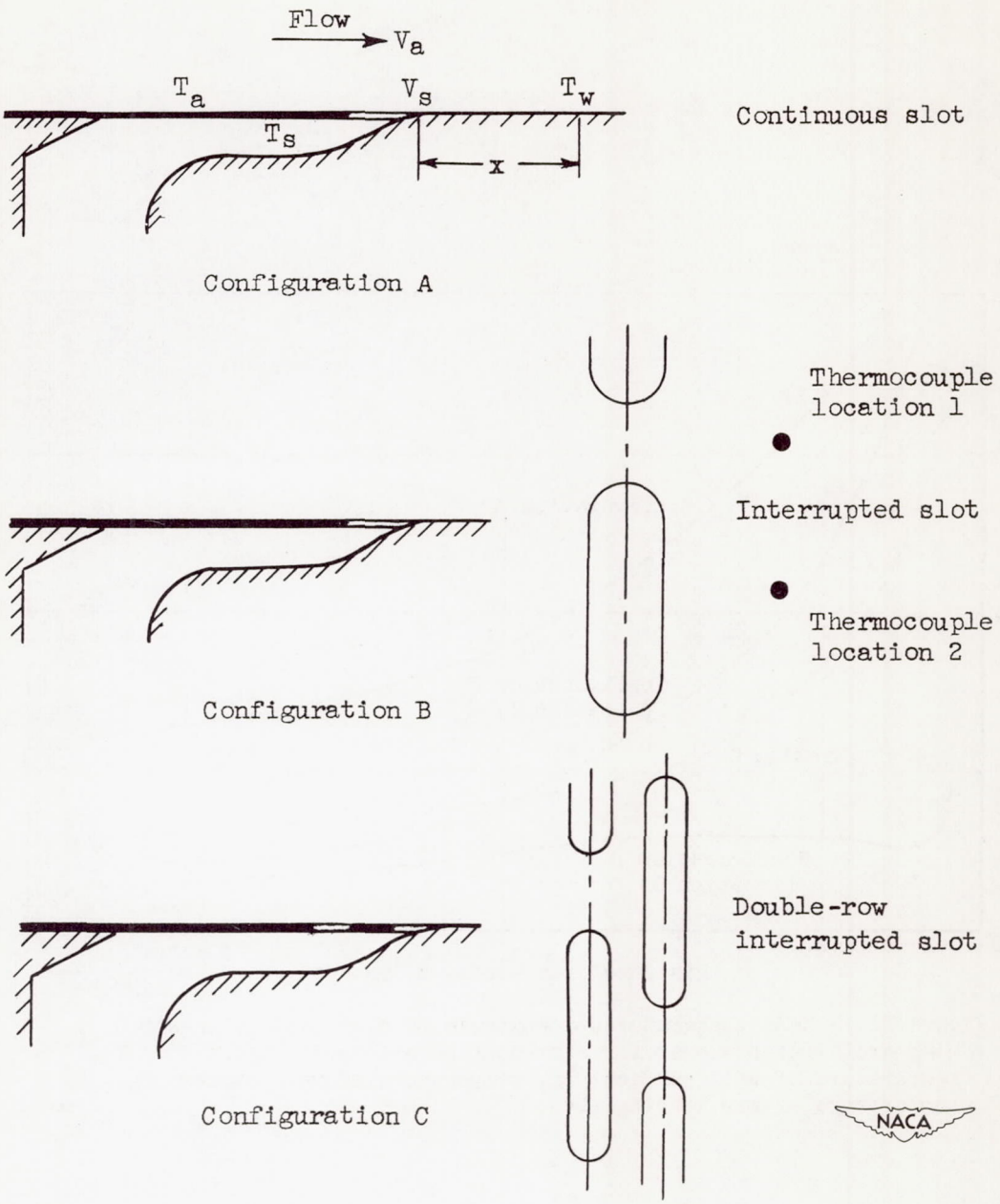


Figure 20. - Slot configurations investigated by Wieghardt (reference 7). T_a, temperature and V_a, velocity in main stream; T_s, temperature and V_s, velocity of air leaving slot; T_w, wall surface temperature; x, distance from slot.

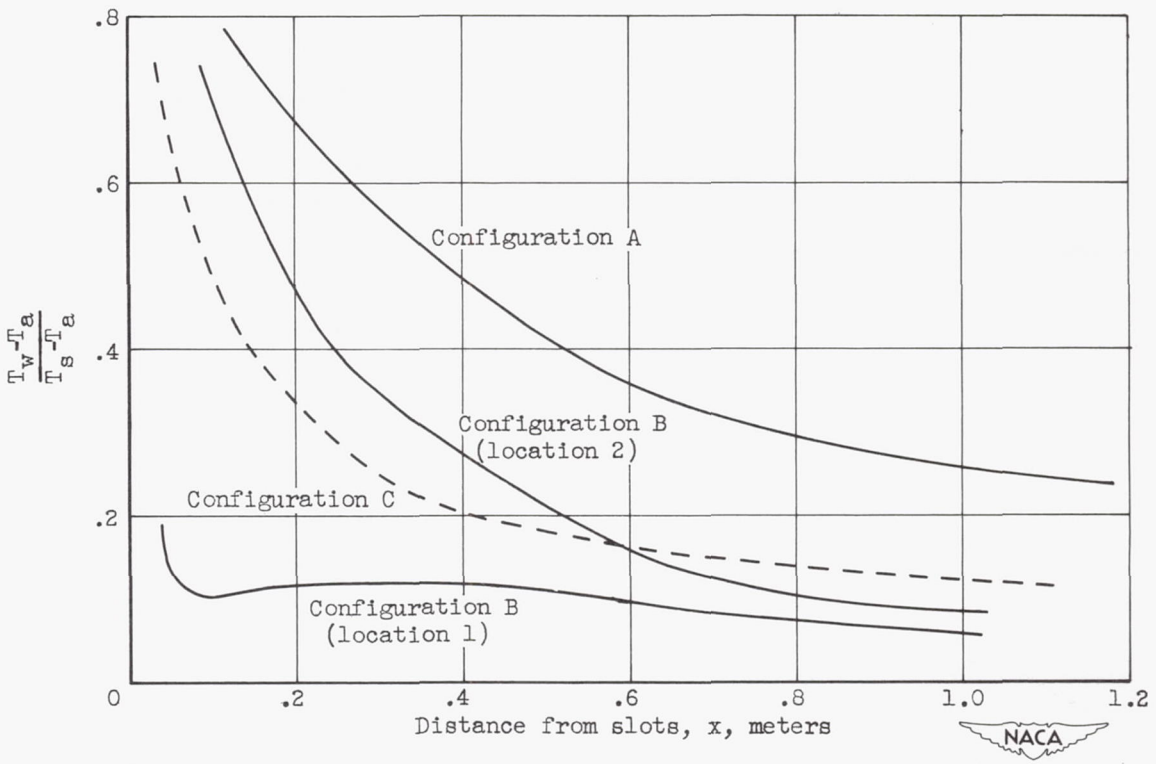


Figure 21. - Wall temperatures downstream of slot exit as measured by Wieghardt (reference 7) for slot configurations in figure 20. T_w, temperature of wall surface; T_a, temperature of main stream; T_s, temperature of air leaving slot.

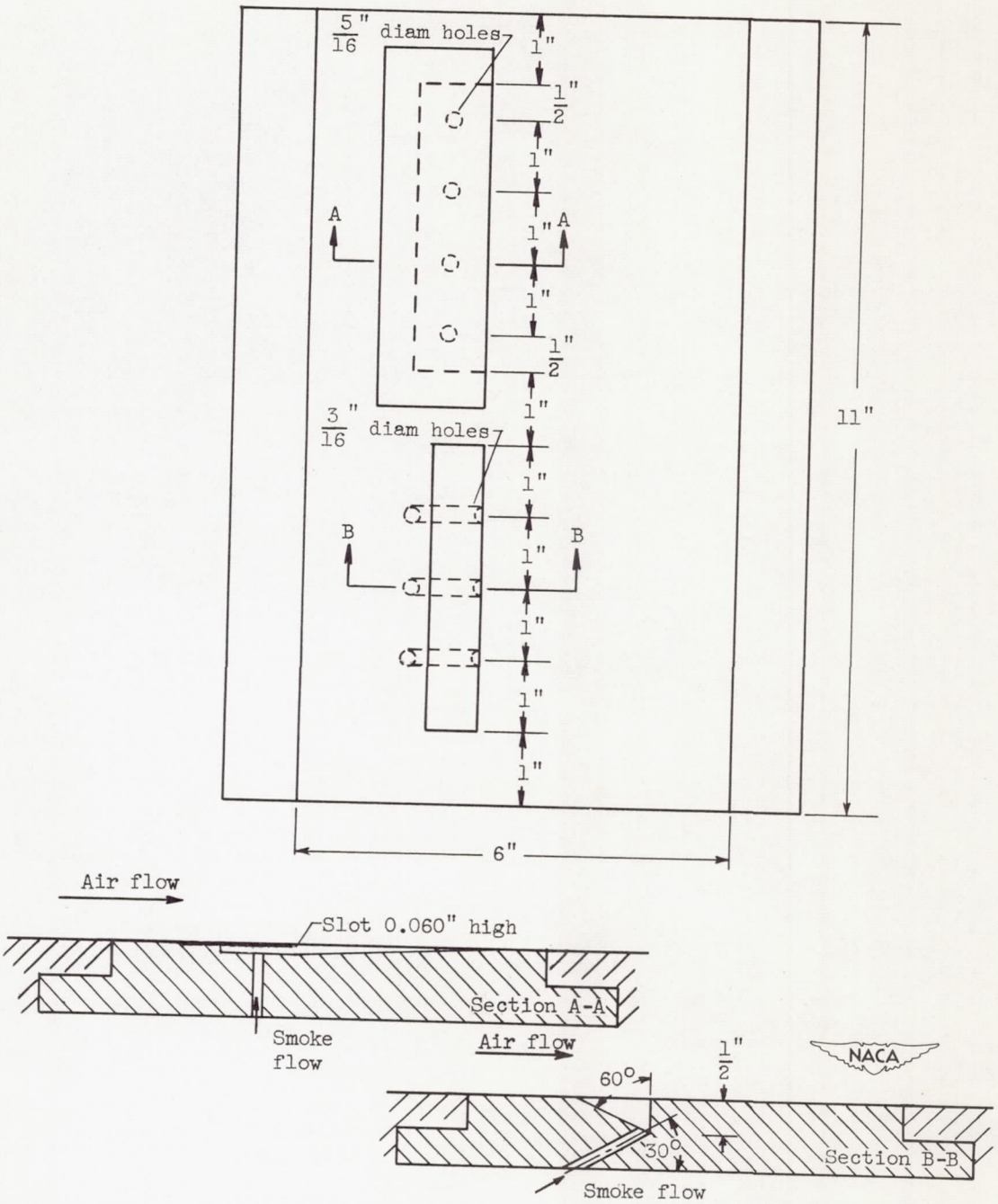


Figure 22. - Trailing-edge test sections. Section A-A; simulated continuous slot; Section B-B, row of holes in deep groove.

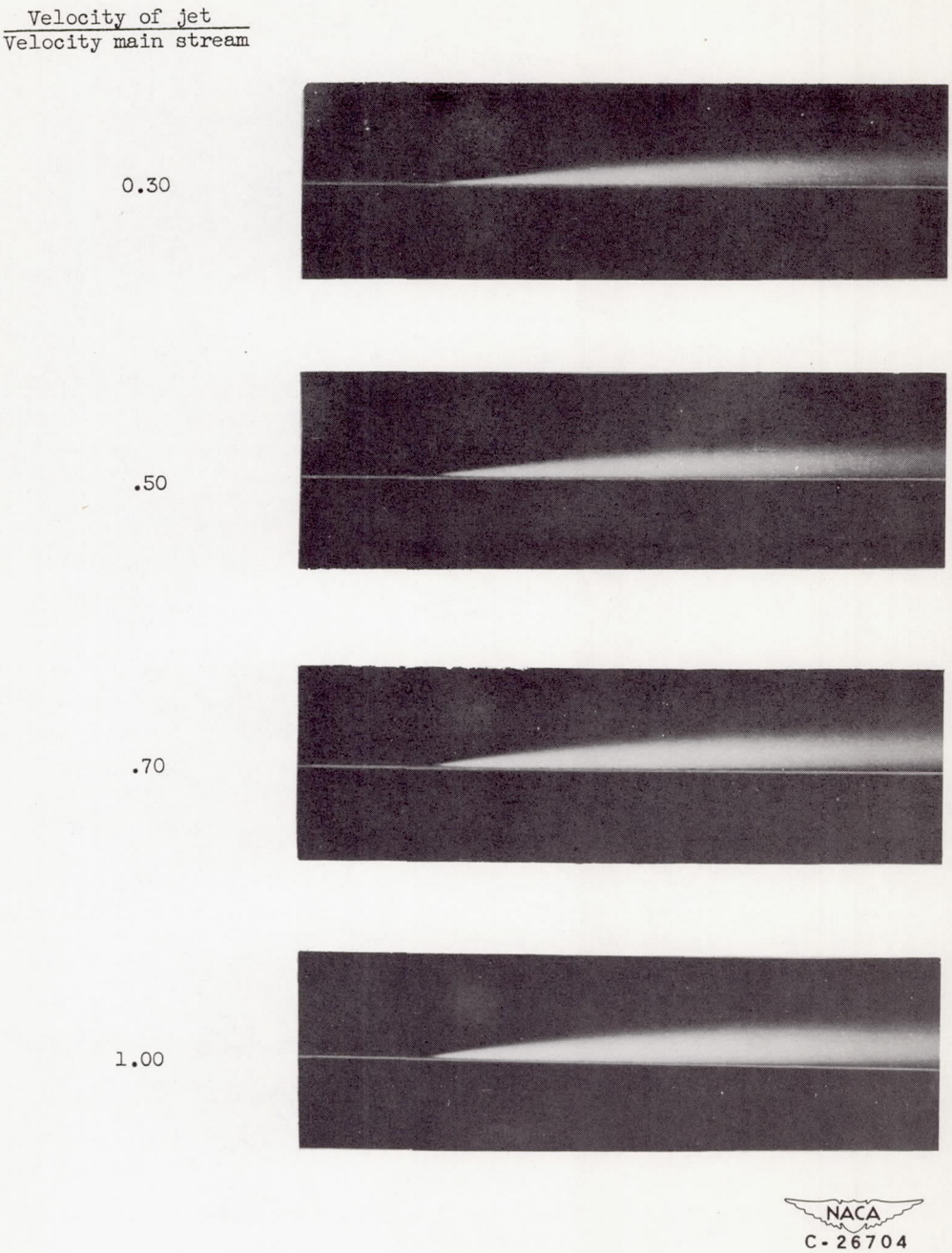


Figure 23. - Smoke jet for simulated continuous slot trailing-edge test section.

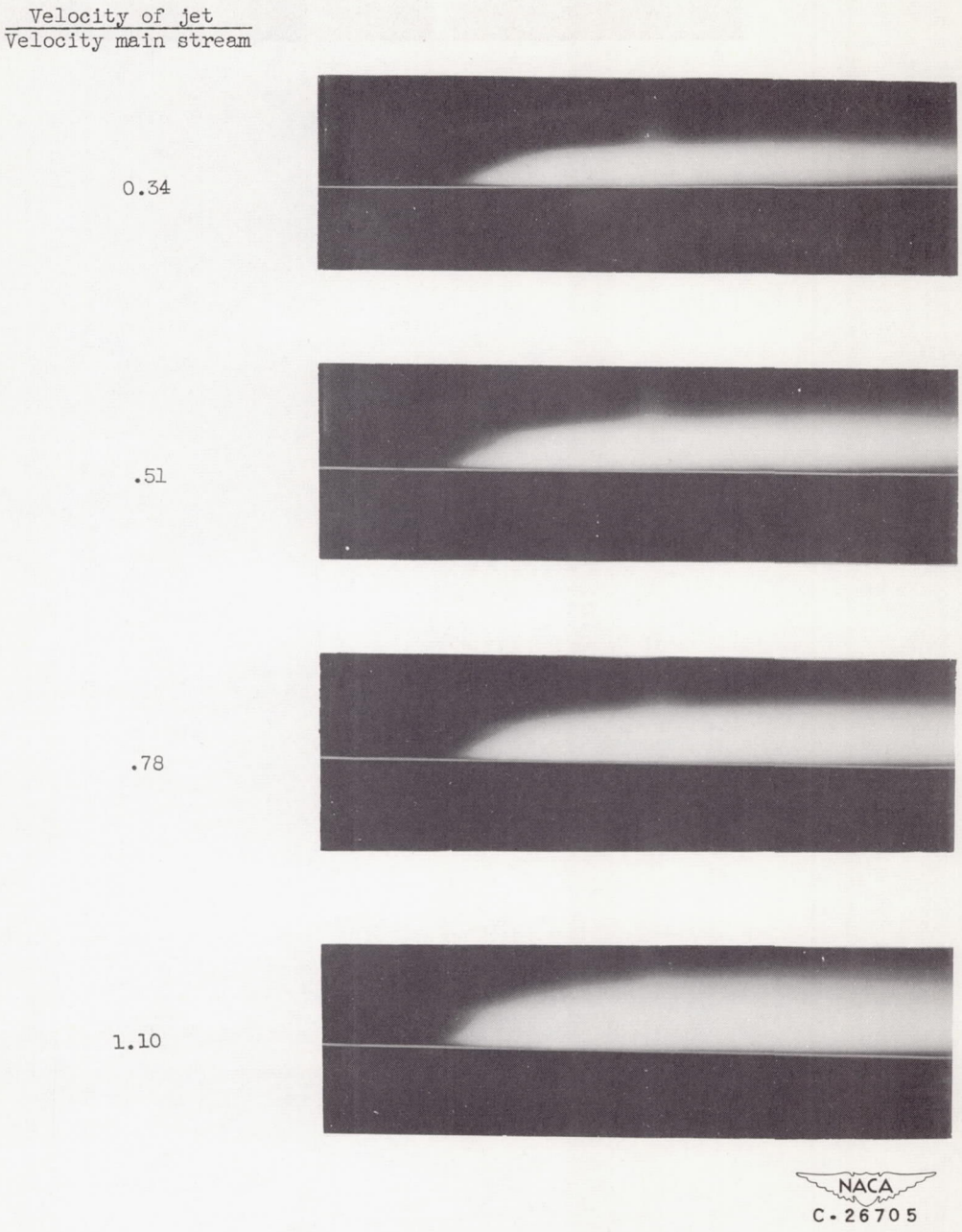


Figure 24. - Smoke jet for row of holes in deep groove trailing-edge test section.

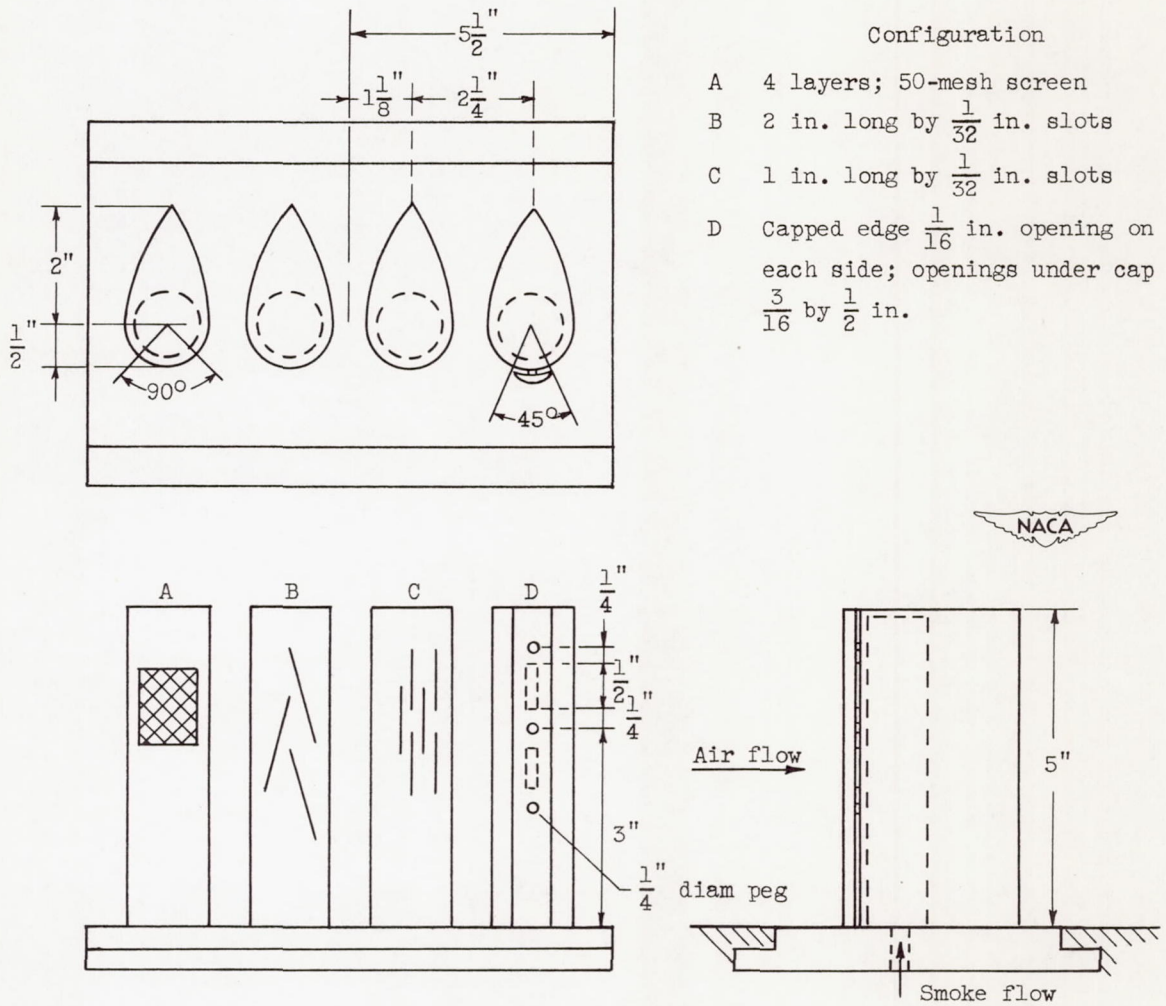


Figure 25. - Leading-edge test section.

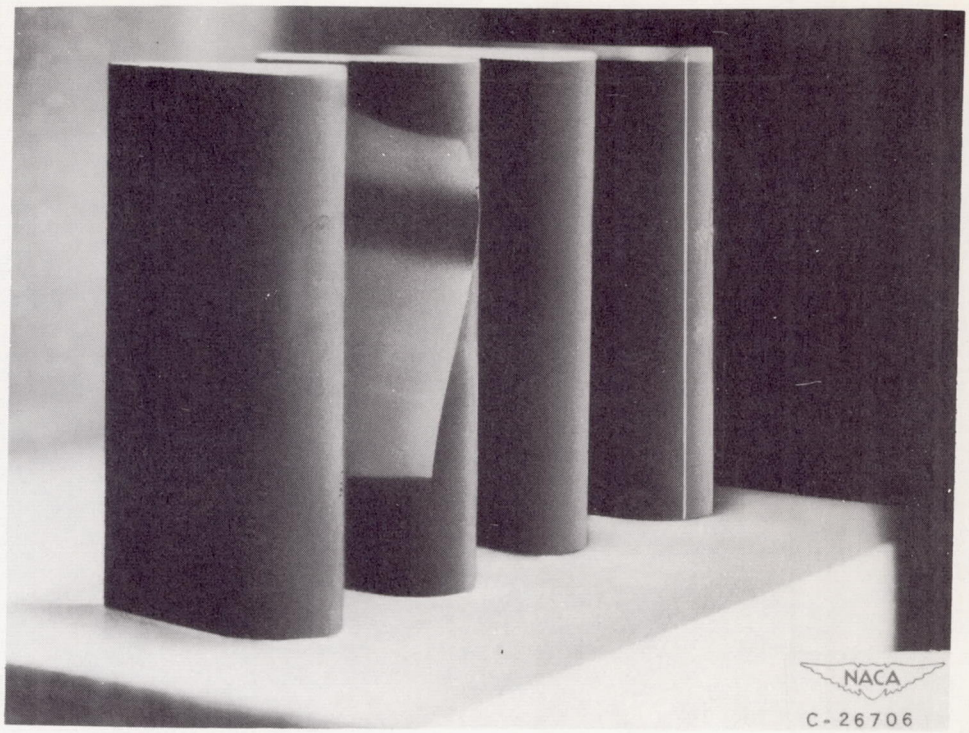


Figure 26. - Smoke film on chevron-slot leading-edge test section. High smoke flow rate.

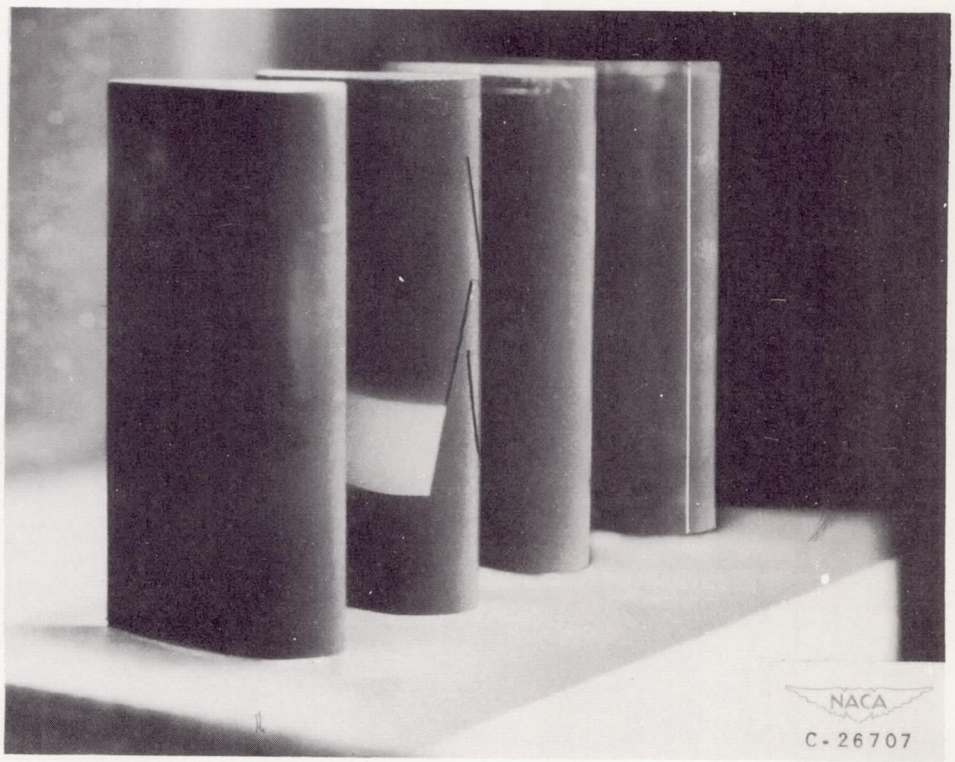


Figure 27. - Smoke film on chevron-slot leading-edge test section. Low smoke flow rate.

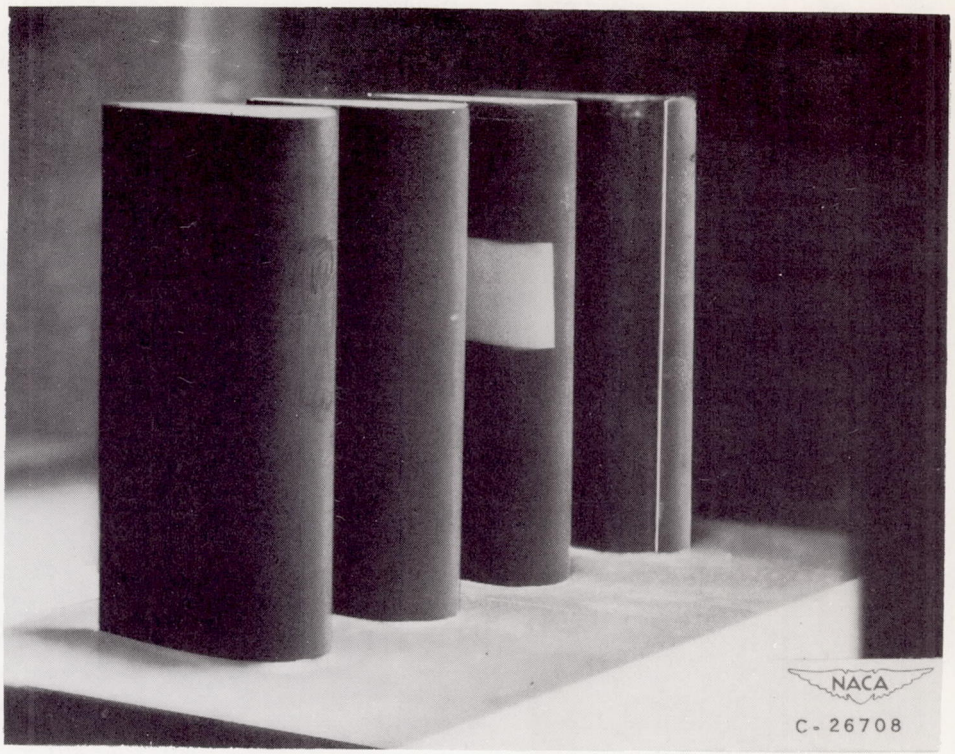


Figure 28. - Smoke film on vertical slot leading-edge test section.

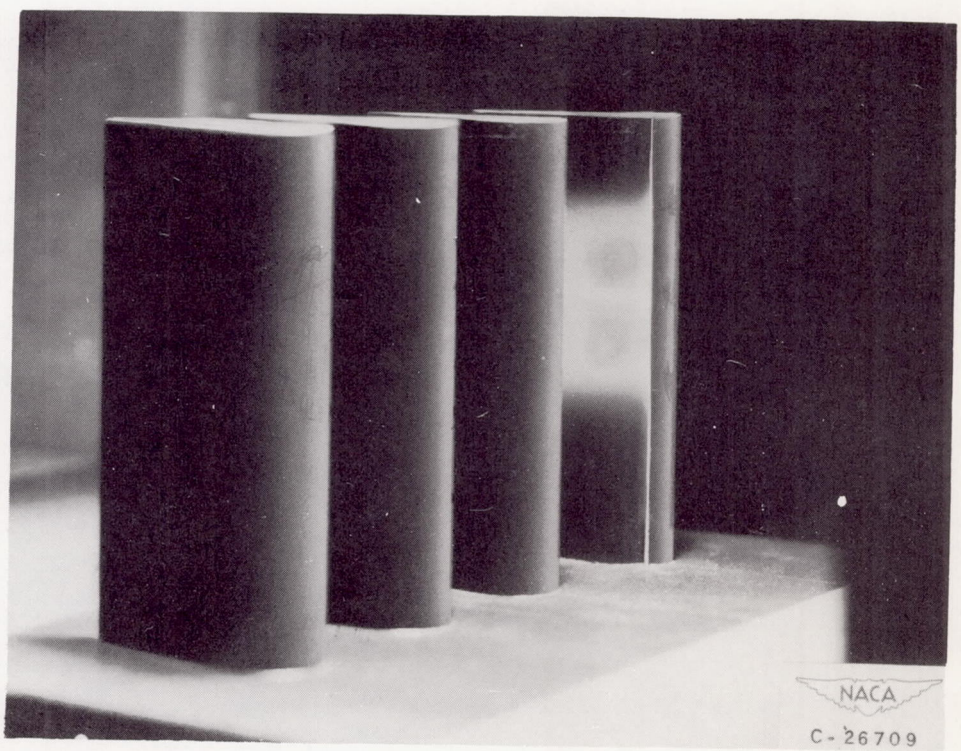


Figure 29. - Smoke film on capped leading-edge test section.

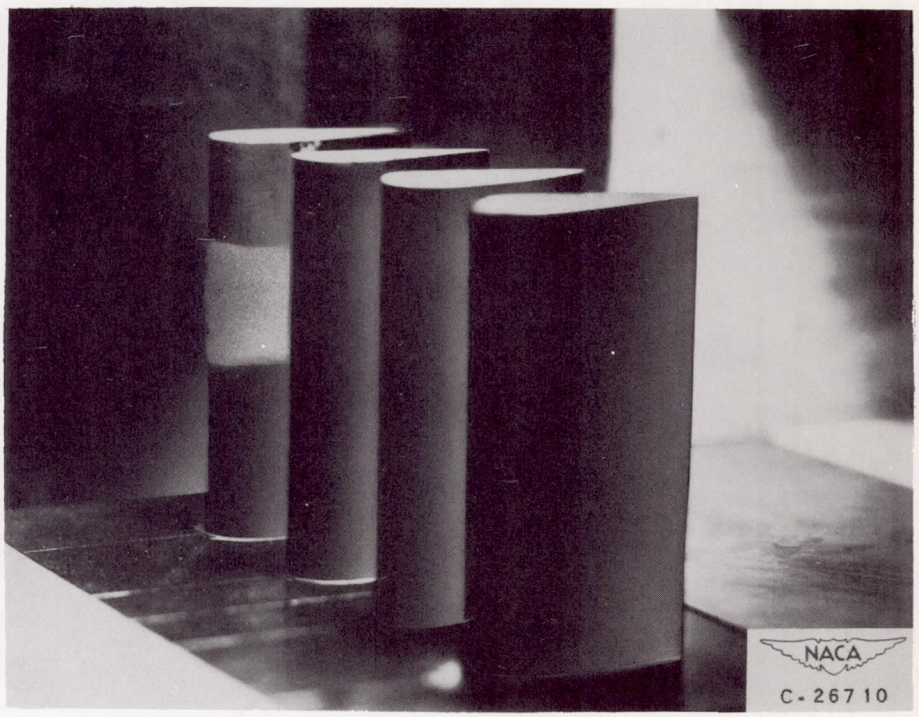


Figure 30. - Smoke film on simulated porous leading-edge test section.